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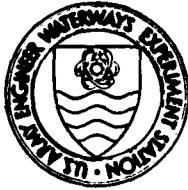
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# MILITARY HYDROLOGY

Report 6

ASSESSMENT OF TWO CURRENTLY "FIELDABLE" GEOPHYSICAL
METHODS FOR MILITARY GROUND-WATER DETECTION

by

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

A Defense Science Board Water Support Task Force concluded that technology shortfalls exist in surface techniques for detection of ground water. These shortfalls in technology were also recognized in a Draft Letter of Agreement (DLOA) for a Subsurface Water Detector. In recognition of the ground-water detection technology shortfalls and in response to the questions raised by the DLOA, a Ground-Water Detection Workshop was held at Vicksburg, Mississippi, in January 1982. Conclusions of the Geophysics Working Group at the

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20. ABSTRACT (Continued).

Ground-Water Detection Workshop were: (a) there are two currently "fieldable" geophysical methods, electrical resistivity and seismic refraction, that are applicable to the ground-water detection problem and may offer a near-term solution to the identified detection technology shortfall, and (b) there are several state-of-the-art and emerging geophysical techniques that may have potential in the far term for application to the ground-water detection problem.

This report is the result of a study to (a) assess the feasibility of using two currently fieldable geophysical methods for military ground-water detection applications, (b) determine the limitations of the complementary use of the methods for the detection application, and (c) determine the level of expertise required for acquiring, processing, and interpreting the geophysical data if the methodology is feasible and the limitations are acceptable. The report presents the results of geophysical surveys at two sites, White Sands Missile Range, New Mexico, and Fort Carson, Colorado.

Locations surveyed at the two sites presented varied geological complexity and ground-water conditions. Results of the surveys demonstrated success, marginal success, and failure in the ground-water detection application.

Study conclusions can be summarized as follows: complementary seismic refraction and electrical resistivity surveys (a) can generally be used successfully for ground-water detection when the water table occurs in unconsolidated sediments and (b) generally cannot be used successfully for detection of ground water in confined rock aquifers. For the case of rock aquifers, a ground-water exploration program is required. The differences between the exploration and detection applications of geophysics are explained in the report.

The study determined that:

a. Rugged, reliable seismic refraction and electrical resistivity instrumentation equipment that is commercially available would require very little adaptation for military ground-water detection application.

b. Rugged field microcomputer systems that are commercially available are suitable for processing and aiding in the interpretation of survey data, and interactive, "user-friendly" computer programs are available for survey data interpretation.

c. Military personnel can be trained to conduct seismic refraction and electrical resistivity surveys; minimum recommended training time is 3 months.

d. Professional expertise is required for final data interpretation.

Feasible deployment options are also considered in the report.

PREFACE

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COL Tilford C. Creel, CE, was Commander and Director of WES during the conduct of this study. Mr. F. R. Brown was Technical Director.

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CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
feet	0.3048	metres
feet per second	0.3048	metres per second
miles (U. S. statute)	1.609347	kilometres
ohm-feet	0.3048	ohm-metres
pounds (mass)	0.4535924	kilograms

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ASSESSMENT OF TWO CURRENTLY "FIELDABLE" GEOPHYSICAL
METHODS FOR MILITARY GROUND-WATER DETECTION

PART I: INTRODUCTION

Background

1. Military hydrology is a specialized field of study that deals
with the effects of surface and subsurface water on the planning and con-
duct of military operations. In 1977, the Office, Chief of Engineers,
approved a military hydrology research program; management responsibil-
ity was subsequently assigned to the Environmental Laboratory, US Army
Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi.

2. The objective of military hydrology research is to develop an
improved hydrologic capability for the Armed Forces with emphasis on ap-
plications in the tactical environment. To meet this overall objective,
research is being conducted in four thrust areas: (a) weather-hydrology
interactions; (b) state of the ground; (c) streamflow; and (d) water
supply.

3. Previously published Military Hydrology reports are listed on
the inside of the front cover. This report is the third that contrib-
utes to the water-supply thrust area, which is oriented toward the devel-
opment of an integrated methodology for rapidly locating and evaluating
ground-water supplies, particularly in arid regions. Specific work
efforts include: (a) the compilation of guidelines for the expedient
location of water for human survival; (b) the development of remote
imagery interpretation procedures for detecting and evaluating ground-
water sources; (c) the adaptation of suitable geophysical methods for
detecting and evaluating ground-water sources; and (d) the development
of water-supply analysis and display concepts.

4. A Defense Science Board (DSB) Water Support Task Force con-
cluded that technology shortfalls exist in surface techniques for de-
tection of ground water.* These shortfalls in technology were also

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* Classified reference. Bibliographic material for the classified
reference will be furnished to qualified agencies upon request.

recognized in a Draft Letter of Agreement (DLOA) for a Subsurface Water
Detector (SSWD) (U. S. Army Engineer School 1981), which called for the
development of a "black box" water detector. The consensus of those who
reviewed the DLOA was that the concept was premature. In recognition of
the ground-water detection technology shortfalls and in response to the
questions raised by the DLOA, a Ground-Water Detection Workshop was held
at Vicksburg, Mississippi, 12-14 January 1982. The workshop was spon-
sored jointly by WES and the U. S. Army Mobility Equipment Research and
Development Command (MERADCOM).*

5. The conclusions of the Geophysics Working Group at the Ground-
Water Detection Workshop were: (a) there are two currently "fieldable"
geophysical methods, electrical resistivity and seismic refraction, that
are applicable to the ground-water detection problem and may offer a
near-term solution to the technology shortfall and (b) there are several
state-of-the-art and emerging geophysical techniques that may have poten-
tial in the far term for application to the ground-water detection prob-
lem. The near-term solution, i.e., the use of currently fieldable
methods, has the potential of significantly reducing the risk of dry
holes during water well drilling operations, but the field operations
are somewhat cumbersome and time-consuming for possible deployment in
support of forward area operations. Development of one or more of the
emerging geophysical techniques offers the possibility of delivering the
desired SSWD or at least something closer to it than the near-term
methodology.

6. The present investigation was initiated in May 1982 to deter-
mine the feasibility of implementing the near-term solution.

Objectives

7. Objectives of this investigation were (a) to assess the feasi-
bility of using two currently fieldable geophysical methods for military

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* In October 1983, MERADCOM became the US Army Belvoir Research and
Development Center.

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ground-water detection applications, (b) to determine the limitations of the complementary use of the methods for the detection application, and (c) to determine the level of expertise required for acquiring, processing, and interpreting the geophysical data if the methodology is feasible and the limitations are acceptable.

Scope

8. The investigation reported here includes the following phases or considerations:

     a. Review of geophysical ground-water detection and exploration concepts.

     b. Evaluation and selection of geophysical equipment.

     c. Selection of two field test sites for demonstration of the geophysical methods for ground-water detection.

     d. Evaluation of data interpretation methods in processing data from the field test sites.

     e. Assessment of the electrical resistivity and seismic refraction methods for military ground-water detection applications and the minimum levels of expertise required for all phases of the operation.

PART II: GEOPHYSICAL GROUND-WATER DETECTION CONCEPTS

Detection Versus Exploration

9.   Geophysical methods are used throughout the world in exploration programs for the assessment and development of ground-water resources.   The geophysical methods predominantly used in these exploration programs are gravity, electrical resistivity, and seismic refraction methods.   Although occasionally only one of these methods will be used in an exploration program, generally at least two are used in a complementary approach.   A geophysical ground-water exploration program normally will use all available borehole and other geological data in order to produce the best possible assessment of the ground-water potential and conditions in an area.

10.   The primary objective of geophysical ground-water exploration is the mapping of subsurface structural and stratigraphic indicators of the possible occurrence of ground water, such as buried river channels, fracture zones in bedrock, confining layers (aquacludes), etc.   Actual detection of the ground-water table with any of the geophysical surveys may be noted but may not be of primary importance in the overall ground-water exploration assessment.

11.   Use of the seismic refraction method to delineate a buried channel in an arid region in western Kansas is illustrated in Figure 1.*
Identification of material type was made by correlation with exploratory borings near each end of the profile.   In this example, the water table was detected by the occurrence of a characteristic seismic velocity (to be discussed later in this part) in the central part of the survey profile.   However, even if the ground-water table had not been detected in this example, the stratigraphic indicators would dictate the greatest ground-water potential for a well placed in the center of the subsurface channel.

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*   A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 4.
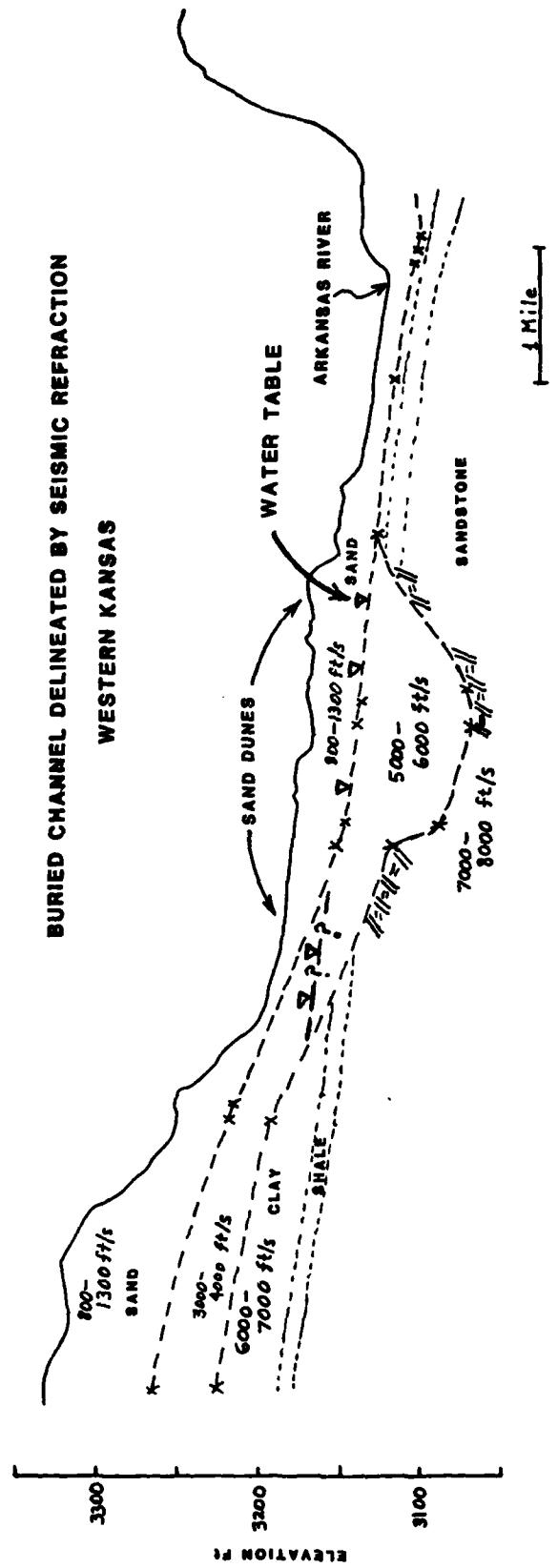
Figure 1. Example of ground-water exploration/detection using the seismic refraction method

12. The expression "ground-water detection" as used in this report, in contrast to ground-water exploration, applies to the concept of detecting the presence (or absence) of ground water and the depth to the water table beneath a given "point" on the surface by conducting one or more types of geophysical tests at that point. In the ideal case, the aquifer thickness and water quality would also be determined. For some cases, information regarding ground-water occurrence and other geological factors might be available, but in general, the assessment of the presence of ground water must rely solely on the geophysical results at the given surface location in the detection scenario. In many cases, geophysical ground-water surveys will probably be required to select a site from among those alternate sites already identified by other methods as having good ground-water potential. Of the three geophysical methods most commonly used in ground-water exploration programs, only two (electrical resistivity and seismic refraction) are applicable to the ground-water detection problem; these two methods and applicable detection principles are considered in the following paragraphs.

Detection Principles

13. A thorough discussion of the physical principles involved in the electrical resistivity and seismic refraction methods is beyond the scope of this report. Useful general references for more detailed information on these methods are Engineer Manual 1110-1-1802 (Department of the Army 1979), Griffiths and King (1969), Parasnis (1979), and Telford et al. (1976). References that particularly address applications of geophysics to ground-water exploration and detection are Zohdy, Eaton, and Mabey (1974) and Geological Survey of Canada (1967).

Electrical resistivity method

14. The electrical resistivity method most often applicable to the ground-water detection problem is vertical resistivity sounding, where the objective is to make electrical measurements at the surface from which the vertical variation of electrical resistivity with depth can be interpreted. The resistivity of a material is numerically equal

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to the resistance of a specimen of the material with unit dimensions and is a fundamental or characteristic geophysical parameter of the material. Although the range of resistivities of geological materials is of the order of 10^{20} ohm-ft, the range commonly encountered in ground-water exploration and detection is 10^5 ohm-ft (0.1 to 10,000 ohm-ft).

15. Most soils and rocks conduct current primarily electrolytically, i.e., through interstitial pore fluid. Thus, porosity, water content, and dissolved electrolytes in the water are the controlling factors in determining resistivity rather than the soil or rock type. A major exception to this generalization are clays, which can conduct current both electrolytically and electronically. The general relation between bulk resistivity ρ_b of a soil or rock and the porosity ϕ (volume fraction), pore fluid saturation S_w (volume fraction of ϕ), and pore fluid resistivity ρ_w can be expressed by the empirical equation

$$\rho_b = c\rho_w\phi^{-m}S_w^{-n} \tag{1}$$

where c , m , and n are constants that depend on the soil or rock type. Below the water table $S_w = 1$ (100 percent saturation). Qualitatively, Equation 1 indicates: (a) as porosity increases, bulk resistivity decreases; (b) as pore fluid saturation increases, bulk resistivity decreases; and (c) as pore fluid resistivity increases, bulk resistivity increases.

16. The most common and successful use of resistivity sounding is for detecting the freshwater-saltwater interface, which will always be detected by the occurrence of a prominent resistivity decrease. Detection of the water table itself is a more difficult problem. Under favorable conditions, the water table will be detected as the top of a conductive or less resistive layer since, except for unusual conditions, even fresh potable ground water is much lower in resistivity than the dry aquifer material. The most favorable conditions will be when the water table occurs in unconsolidated sediments with little clay content. Dry silts, sands, and gravels will have resistivities of 1000 ohm-ft and greater; for fresh water, the resistivity at the water table will

decrease to a range of 50 to 200 ohm-ft in areas such as the southwestern
United States. In sediments with considerable clay content, the resis-
tivity contrast will be much smaller and may be undetectable. At a
freshwater-saltwater interface, the resistivity of the aquifer will
decrease considerably, perhaps to $\tilde{<}1$ ohm-ft. Zohdy et al. (1969) and
Zohdy, Eaton, and Mabey (1974) adopt a qualitative criterion of $\rho_b \sim$
30 ohm-ft to differentiate freshwater from saline ground-water conditions
in a large ground-water assessment program at White Sands, New Mexico.
Clays can have resistivities intermediate to the resistivities of highly
saline and fresh aquifer conditions.

Seismic refraction method

17. The seismic method applicable to the ground-water detection
problem (in the near term) is the refraction method. From a seismic
refraction survey at a given location, it is possible in principle to
determine depths to interfaces between materials with contrasting bulk
density and seismic velocity and to determine the seismic velocities of
the different materials. Generally, only compression- or P-wave veloci-
ties are easily determined from seismic refraction surveys.

18. The physical principle involved in detection of the water
table by seismic methods is that the compression-wave velocity of satu-
rated sediments is considerably greater than the same sediments in dry
or only partially saturated conditions. Typically, the compression-wave
velocity will increase from 1000-2000 ft/sec to 4500-5500 ft/sec at the
water table, where the water table occurs at shallow depths ($\leq$100 ft)
in unconsolidated sediments (silts, sands, and gravels). The occurrence
of a characteristic 5000 ft/sec-velocity at shallow depths at a site
generally is strongly indicative of a ground-water table, although some
weathered rocks and massive clay deposits also exhibit this velocity.

19. If the water table occurs at greater depths (>100 ft, for
example), the seismic velocity of the saturated sediments can be as
high as 7500 ft/sec; in these cases, the velocity of the unsaturated
sediments just above the water table can be as high as 4000 ft/sec. The
smallest velocity contrast at the water table will occur in very fine-
grained sediments, where the velocity contrast can be as small as

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500 ft/sec. When the water table occurs as an unconfined surface in rock, there will always be a velocity increase at the water table, although it may be small. Where the ground water occurs in a confined rock aquifer, there will be little in the seismic data to suggest the presence of ground water without independent or complementary information. Whether the water table in an unconfined aquifer is detected depends on the thickness of the saturated zone above high-velocity rock. In some cases, where the contrast in seismic velocity between rock and saturated sediments is large and the saturated zone is thin relative to its depth, the water table refraction will not be detected in an "ordinary" seismic refraction interpretation due to a blind zone problem (see Redpath 1973 and Zohdy, Eaton, and Mabey 1974).

Complementary methods

20. The resistivity and refraction methods are complementary in the sense that they respond to or detect different physical properties of geologic materials. Both methods can detect the water table, and hence, the presence of ground water under certain conditions. In cases where both methods detect the water table, one method serves to confirm the results of the other or to resolve ambiguities. Also, certain conditions, such as the presence of a freshwater-saltwater interface, can be detected by one method but not the other. The conclusions portion of this report presents examples from the field demonstration tests of cases in which the complementary method approach probably would be successful, possibly would be successful, or would not be successful.

21. Generally, when depths to interfaces determined by geophysical methods are compared to "ground truth" data from nearby boreholes, the agreement is within ±10 percent for the seismic refraction and ±20 percent for the electrical resistivity method. Of course, the difference between the actual interface depth and geophysical interface depth can occasionally be greater due to the effects of blind zones and velocity inversions (departures from the normally assumed case where seismic velocity increases with depth) in seismic refraction interpretation and highly equivalent layers in electrical resistivity interpretation (Department of the Army 1979; Telford et al. 1976; Zohdy, Eaton, and Mabey

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1974). The problem of geophysical determination of the water table
depth is complicated by the physical nature of the "interface." The
geophysical interface often may be within the capillary zone. The
velocity and resistivity interfaces may be different, and neither may
agree with the standing water depth in a borehole (and the standing water
depth itself may be different from the actual water table). The dif-
ference in geophysical and borehole water table depth determinations
should be greatest in fine-grained sediments and least in coarse-grained
sediments.

PART III: FIELD PROCEDURES AND EQUIPMENT SELECTION

Electrical Resistivity Method

Field procedures

22. The surface electrical resistivity methods considered in this
study involve linear four-electrode geometries (arrays). Two of the most
common electrode arrays are illustrated in Figure 2. In each of the

WENNER ELECTRODE ARRAY

SCHLUMBERGER ELECTRODE ARRAY
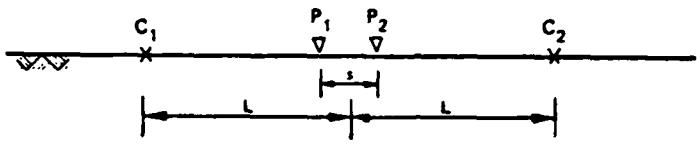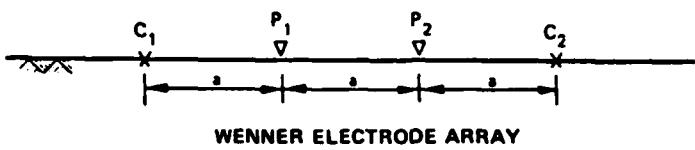
Figure 2. Two four-electrode arrays

arrays, an electrical current I is input to the ground at electrodes
C_1 and C_2 . Electrodes P_1 and P_2 are used to measure a potential
difference ΔV . The following equation can be used to calculate an
apparent resistivity ρ_A :

$$\rho_A = K_G \left(\frac{\Delta V}{I}\right) \tag{2}$$

where K_G is a geometric factor that depends on the array type and
electrode spacings within the array. For the Wenner array, $K_G = 2\pi a$;
for the Schlumberger array $K_G = \pi s \left[(L/s)^2 - 1/4\right]$, where $L = \overline{C_1 C_2}/2$
and $s = \overline{P_1 P_2}$ (generally $L > 5s$) .

23. The resistivity given by Equation 2 is called an apparent
resistivity since it may not actually be the true resistivity of any of
the subsurface materials. This fact can be illustrated by a conceptual
example: consider a layer of soil over rock that is very thick. If a

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Schlumberger or Wenner electrode array is used to study the example just presented, the following facts can be stated: (a) for electrode spacings a or L much smaller than the soil layer thickness, the measured apparent resistivity (ρ_A) approaches the true resistivity of the soil (ρ_1); (b) for electrode spacings a or L much greater than the soil layer thickness, the apparent resistivity approaches the true resistivity of the rock (ρ_2); and (c) for a or L values between these two extremes, the apparent resistivity will be intermediate in value (i.e., the measured apparent resistivity will be some type of volume average of ρ_1 and ρ_2, with the volume included in the measurements increasing with a and L).

24. In vertical resistivity sounding, the electrode array is expanded symmetrically about a center point, and variations in apparent resistivity as the electrode spacing increases are assumed to reflect changes in true resistivity as a function of depth beneath the surface point of symmetry of the array. The objective in vertical sounding interpretation is to determine the variation in true resistivity versus depth from the apparent resistivity versus electrode spacing data. The result will generally be a layered model consisting of layer thickness and associated true resistivities. Interpretation is usually accomplished by curve matching (i.e., matching field data curves with standard curves) or by the use of a resistivity inversion computer program. Useful discussions of resistivity theory, field methods, interpretation procedures, and case histories can be found in Telford et al. (1976), Department of the Army (1979), and Zohdy, Eaton, and Mabey (1974).

25. For the Wenner array, all four electrodes must be moved for each measurement; for the Schlumberger array, only the two current electrodes are moved for each measurement (except as described below). Thus, there are advantages in terms of field effort in using the Schlumberger array. The resistivity soundings presented in this report were accomplished using the Schlumberger array. Generally, a minimum of six measurements per decade of electrode spacing (L ranging from 10 to 100 ft, for example) are required. If the minimum number is used, the measurements should be made at electrode spacings that are approximately

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equally spaced on a logarithmic scale (e.g., 10, 14, 20, 30, 50, 70, 100, 140, etc.). During the course of conducting a Schlumberger sounding, the potential difference between P_1 and P_2 may become too small to measure with the resistivity instrument, and the spacing P_1P_2 must be increased before continuing. As a rule of thumb, the sounding should be carried out to an L-spacing equal to at least four times the desired depth of investigation.

26. Field measurements, which may be ΔV and I individually or the ratio $\Delta V/I$, are converted to apparent resistivities ρ_A using Equation 2. The ρ_A are then plotted versus L on log graph paper. The data are then ready for interpretation.

Equipment

27. The equipment required for the resistivity method consists of (a) a power supply, (b) instruments for measuring current and potential difference, (c) four stainless steel electrodes, (d) cable reels and cable, (e) nonconducting tapes for distance measurements (or other method for determining distances such as precision odometers), and (f) two-way portable communications equipment (up to 1-mile range). For the present investigation, cable reels equipped with cable sufficient for a maximum L-spacing of 2000 ft were used. Figure 3 shows the resistivity instrument

Figure 3. Resistivity instrument selected for fieldwork

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selected for the fieldwork. The instrument is a microprocessor-controlled signal-averaging system capable of depths of investigation of 1000 ft or greater under most field conditions. A system of "beeps" and error codes communicates with the operator, making the instrument very easy to use with minimal training. Power for the instrument is supplied by rechargeable 12-V batteries, and the entire system (including all accessory equipment) is easily portable in a single "jeep-size" vehicle. Total equipment weight for the resistivity field system in about 110 lb.

Personnel requirements

28. A minimum of three field personnel are required for conducting a Schlumberger resistivity sounding. Nonprofessional personnel can be trained to conduct the field surveys. A minimum training period of 6 weeks in field procedures, equipment operation, data processing, elementary geological principles, and elementary resistivity surveying principles is recommended.

Seismic Refraction Method

Field procedures

29. The seismic refraction method involves the generation, propagation, and detection of seismic waves. Seismic waves are generated in two ways in surveys for ground-water detection applications: impact sources (e.g., weight drop or hammer blow) and explosive sources (e.g., dynamite, exploding bridge-wire detonators, and air guns*). Detection of the seismic waves is generally by velocity transducers called geophones, which are connected to a seismograph that amplifies and displays the geophone output. The objective of the seismic methods is to deduce properties of the media through which the seismic waves pass from properties of the detected wave forms (primarily the arrival times of various events or types of waves at the geophones).

30. The seismic refraction method is a survey technique in which the source locations and geophones are along a common line. Figure 4 illustrates the concept of the seismic refraction method, where the

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* Air guns generate seismic waves by a sudden release of compressed gas.

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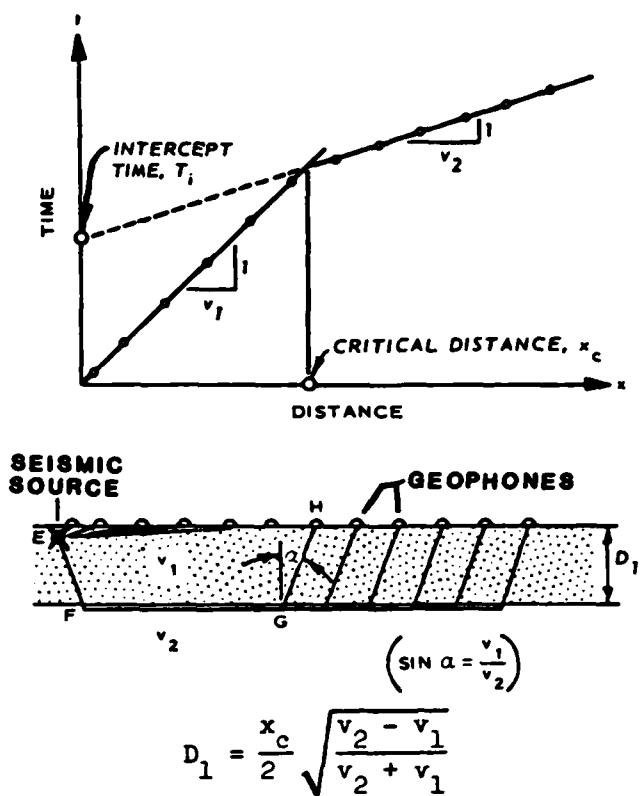
Figure 4. The seismic refraction method,
illustrated by a simple two-layer case
with plane, parallel boundaries, and the
corresponding time-distance plot (after
Redpath 1973)

time-distance plot represents the arrival times of the first event at
each geophone location. The first event at a given geophone will be due
to a wave that propagates directly from the source or to a wave that is
refracted along an interface with a higher velocity material. The ar-
rival time-distance data generally will define a straight line segment
for each subsurface layer. The first-arrival time-distance plot can be
interpreted to give the velocities of subsurface soil/rock layers and
depths to interfaces. Figure 4 illustrates the analysis for the simple
case of two horizontal layers (Department of the Army 1979).

31. For the case of three horizontal layers, the analysis of the
time-distance plot to yield la.er velocities and interface depths is

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still tractable by manual methods. Also, the case of two layers where the interface dips relative to the surface can be similarly analyzed using manual methods (Department of the Army 1979, Telford et al. 1976). However, for the cases of greater than three horizontal layers and greater than one dipping interface, a programmable calculator or a micro-computer is desirable for the interpretation. The presence of dipping layers is indicated by an examination of the time-distance plots from forward and reverse "shooting" along a seismic survey line, i.e., from data obtained by using a source at each end of the geophone line. Figure 5 illustrates the appearance of the time-distance plot for a two-layer case with dipping interface, where the apparent velocity of the second layer is always greater when "shooting" in the up-dip direction.

32. In the past, seismic refraction data processing has involved
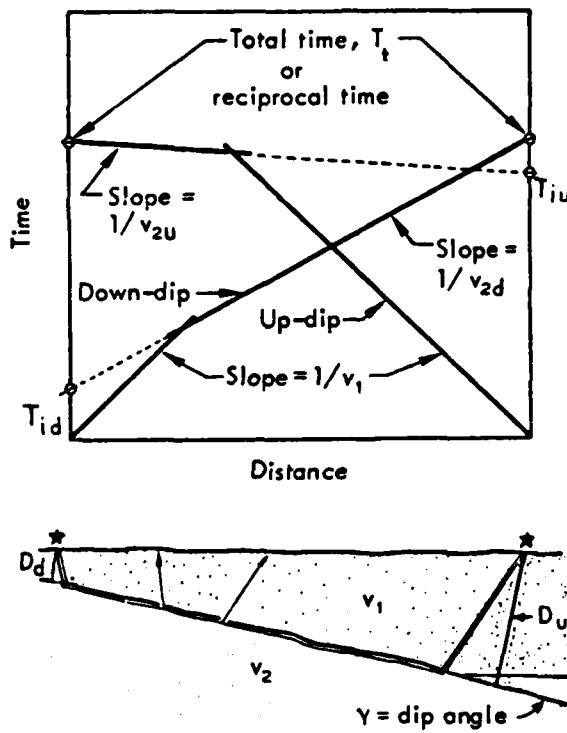
Figure 5. Example of dipping inter-
face and concepts of "reverse shoot-
ing" and "apparent velocity" (after
Redpath 1973)

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manual "picking" of first-arrival events and scaling arrival times from analog records. The time-distance data were then manually plotted, and straight-line segments were fit to the data if possible. Velocities were calculated as the inverse of the slopes of the line segments. Interface depths and dips were then determined manually. This procedure is still common, particularly when refraction survey data are processed and interpreted in the field. However, the availability of digital seismographs (such as the one shown in Figure 6) and powerful microcomputers (such as the one shown in Figure 7) now makes it possible to automate much of the seismic data-processing and interpretation procedure and to accomplish it expeditiously in the field.
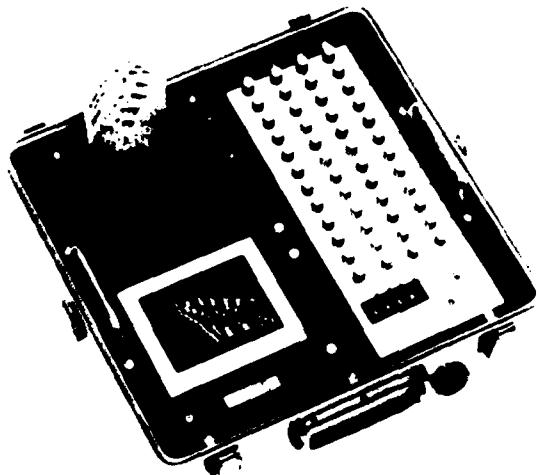
Figure 6.   Digital seismograph selected
for fieldwork

Equipment

33.   The equipment required for the seismic refraction method consists of (a) a multichannel seismograph, (b) seismic sources, (c) geophones, and (d) seismic cables. For the present investigation, two 12-channel seismographs such as the one pictured in Figure 6 were coupled together, although 24-channel seismographs are available with similar features. The seismograph displays output from all 12 (or 24) channels

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Figure 7. Completely self-contained
field microcomputer

on a CRT display and a built-in printer can produce a hard copy. Also,
the seismograph stores the data in digital form and can record the data
on a companion cassette recorder.

34. For depths of investigation of approximately 50 ft or less,
a sledgehammer blow can be used as a seismic source; for greater depths
of interest, an explosive source is required (1- to 3-lb TNT-equivalent
is sufficient for depths of investigation to approximately 600 ft).

35. Geophones are readily available in several acceptable types.
Typically, 30 geophones are required (24 for each test plus 6 spares).
Seismic cables are multiconductor, with geophone takeouts at constant-
spacing intervals along its length. The commonly available geophone
takeout intervals of cable for seismic refraction work are 10, 25, 50,
and 100 ft. Typically, two 12-takeout seismic cables are utilized to
form a 24-geophone refraction spread, and one or more spreads are used
for each seismic survey line, with the required length of the seismic
line determined by the desired depth of investigation (the seismic re-
fraction line length should be at least four times the desired depth of
investigation). The total weight of the equipment required for seismic
refraction surveying is about 350 lb and the equipment is easily trans-
portable in a jeep-size vehicle.

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Personnel requirements

36. Three field personnel are required for conducting seismic re-
fraction surveys. Nonprofessional personnel can be trained to conduct
the field surveys. A minimum training period of 6 weeks in field pro-
cedures, equipment operation, elementary seismic surveying principles,
seismic event recognition, data quality assessment, data processing,
and elementary geological principles is recommended.

Data Processing and Interpretation

Techniques and computer programs

37. Some aspects of the data-processing and interpretation require-
ments for seismic refraction and electrical resistivity survey data have
been discussed in the preceding paragraphs. A detailed discussion of
the techniques involved in data processing and interpretation is beyond
the scope of this report, although the concepts are illustrated in Part
IV with the data acquired in the present study. Butler et al. (1982)
discuss in detail the data-processing and interpretation techniques used
in this study. The seismic refraction data were processed on a WES in-
house microcomputer facility, while the resistivity data were processed
in an interactive time-sharing mode on the WES mainframe computer. The
seismic refraction computer programs are in BASIC language and can be
easily converted to run on the field microcomputer discussed in para-
graph 39. The resistivity interpretation computer programs are in
FORTRAN language and would require more effort to convert to BASIC
language for use on a field microcomputer.

38. Two additional resistivity computer programs, both in BASIC
language, were evaluated in the present study. Selected resistivity
sounding data from the field study were interpreted using a U. S. Geo-
logical Survey (USGS) computer program on a USGS in-house microcomputer
(Zohdy 1975, Bisdorf 1983*). The second additional resistivity interpre-
tation program (ABEM program) is written especially for the field

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* The letter report by Bisdorf (1983) is included as Appendix A to this
report.

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microcomputer discussed in paragraph 39 (Atlas Copco 1980). The ABEM
program is very similar in concept and operation to the WES interpreta-
tion program; the USGS program is different in that it does not require
the input of an initial (first approximation) model* for the subsurface.

Computer requirements

39. Figure 7 shows a microcomputer suitable for field use for
processing resistivity and refraction data. The field microcomputer is
completely self-contained with integrated CRT display, printer, and data
cassette reader/recorder. Generally, a microcomputer with 32K bytes RAM
(random-access memory) or greater is required; an integral or peripheral
disk drive for long-term mass data storage is desirable but is not
essential.

Personnel requirements

40. Nonprofessional personnel can be trained to process elec-
trical resistivity and seismic refraction data using existing, user-
friendly computer programs. Minimum recommended training time is
2 weeks, which is included in the 6-week training periods estimated for
both the seismic refraction and electrical resistivity methods. Gen-
erally, however, individuals processing the data have ready access to
professional geophysicists or more experienced processors who can assist
with difficult or nonroutine data sets; examples of difficult data sets
are the resistivity data from test site locations HTA-1 and B-30, which
are discussed in Part V. The results of the data processing and inter-
pretation are geophysical models (see Part V).

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* The term "model" as used in this report refers to a representation of
the subsurface in terms of layers described by geophysical parameters:
thickness, resistivity, seismic velocity. This geophysical model is
deduced by interpretation of field survey data.

PART IV: FIELD STUDIES

Selection of Field Sites

41. Two field sites were selected as representative of two common aquifers: an unconfined alluvial aquifer and a confined (artesian) rock aquifer. White Sands Missile Range, New Mexico, was selected as the alluvial aquifer site, and Fort Carson, Colorado, as the confined rock aquifer site.

42. Five locations (MAR, B-30, HTA-1, SW-19, and T-14) were selected at the White Sands site, as shown in Figure 8. Each location is near a water supply well, test well, or borehole, so that water table depths are known and some boring log information is available. The five locations have water table depths ranging from approximately 60 to 450 ft and water resistivity varying from fresh ($>$85 ohm-ft) to brackish ($<$1 ohm-ft) (Cruz 1981). Plate 1 is a general site map showing topographic features and the five survey areas.

43. The shallowest depth to water at the five locations occurs at HTA-1, where a thin layer of sediments covers a weathered granite rock surface in the northwestern part of the Headquarters area reentrant. At the other four locations, which are in the Tularoosa Basin, the depth to rock is much greater. Stratigraphic test well T-14 was drilled to a depth of 6000 ft without penetrating rock. Bolson (valley fill) sediments at the MAR, B-30, and T-14 locations consist of clay, silt, sand, and gravel, with the amount of fine sediments decreasing toward the west side of the Tularoosa Basin until, in the vicinity of supply wells SW-19 and SW-20, the material is predominantly sand and gravel. Boring log information and other available data are summarized in Part V.

44. One location near White Butte at the Fort Carson, Colorado, site was selected (see Figure 9). A well at this location produces good quality water from the Dakota Sandstone (Lower Cretaceous) aquifer; depth to the top of the aquifer is approximately 270 ft and the thickness is approximately 100 ft (see Part V, Figure 36, for boring log information). The aquifer is confined on both top and bottom by shale layers. The
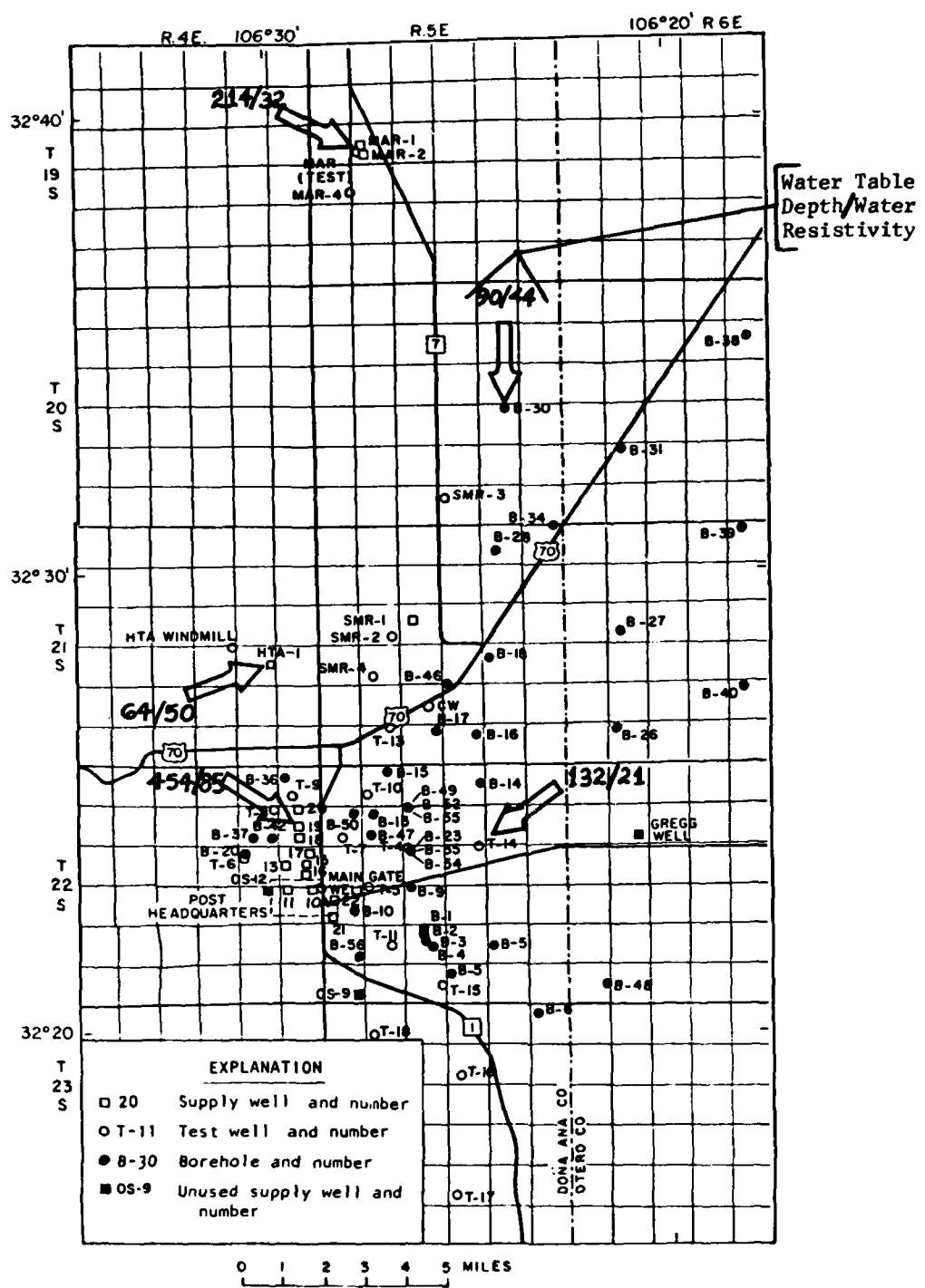
Figure 8. Geophysical survey locations--White Sands Missile
Range, N. Mex. Data presented for each site include water
table depth (ft) and water resistivity (ohm-ft) (from Cruz
1981)

1 Mile

0   .1   .5   1
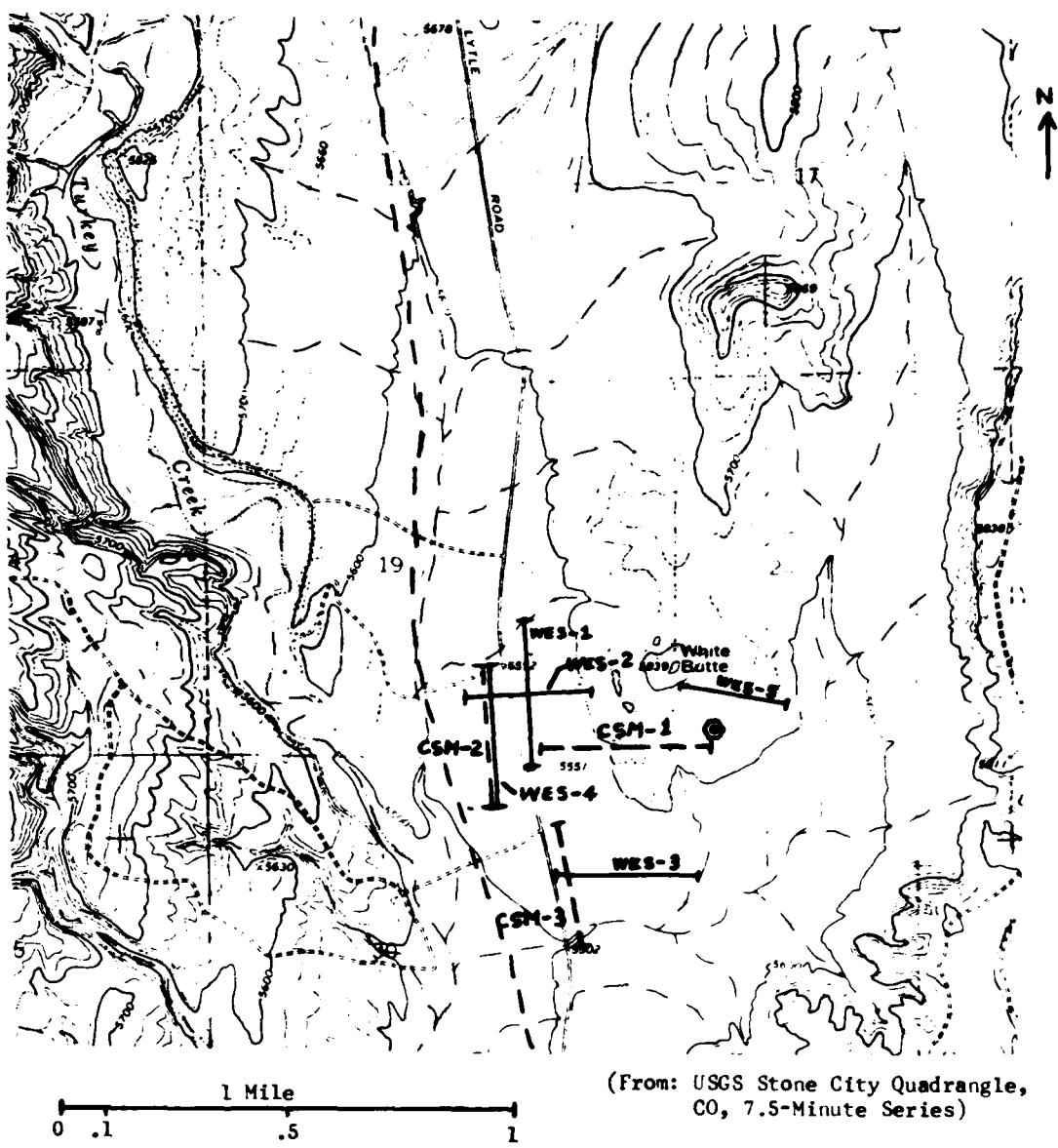
Figure 9. Fort Carson survey layout

Dakota Sandstone outcrops approximately 0.7 mile to the west of the White Butte location and has a regional dip to the east of about 330 ft/ mile. Plate 2 shows the geologic structure and stratigraphy of the Fort Carson area (Dardeau and Zappi 1977). Due to the rugged topography and complex near-surface geology at the well site, geophysical surveys were conducted about 0.5 mile to the west and about 0.5 mile to the

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south, in addition to near the well site itself. Surveys were con-
ducted parallel to the strike of the Dakota Sandstone (north-south) and
perpendicular to the strike (i.e., east-west or parallel to the dip),
as shown in Figure 9.

Geophysical Field Programs

45. Fieldwork at the two sites was conducted by WES and the Colo-
rado School of Mines (CSM). In addition, resistivity data from recent
fieldwork conducted by the USGS at one of the White Sands locations was
provided for use in this study. Details of the field programs at the
two sites are summarized in the following paragraphs.

White Sands geophysical program

46. Table 1 summarizes the geophysical surveys performed at the
White Sands site. Location numbers correspond to the well or borehole
designations, as shown in Figure 8. For the seismic refraction surveys,
the survey line length refers to the total shotpoint-geophone spread
length; for the resistivity surveys, the survey line length refers to
the maximum electrode spacing (L-spacing shown in Figure 2) for the
sounding.

Table 1

White Sands, N. Mex., Geophysical Program

Location	Survey Type	Performing Agency	Survey Line Length, ft	Comments
HTA-1	Refraction	WES	240	
		CSM	330	
	Resistivity	WES	600	
B-30	Refraction	WES	360	
	Resistivity	WES	800	Both Schlumberger and Wenner electrode arrays used at this location
T-14	Refraction	WES	540	
		CSM	600	Perpendicular to WES refraction and resis- tivity lines

(Continued)

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Table 1 (Concluded)

Location	Survey Type	Performing Agency	Survey Line Length, ft	Comments
	Resistivity	WES	1000	
MAR	Refraction	CSM	825	
	Resistivity	USGS	4000	USGS sounding location does not coincide with CSM survey location
SW-19	Refraction	WES	1800	
		CSM	1650	
	Resistivity	WES	1800	Approximately perpendicular to WES and CSM refraction lines and centered about 500 ft west of Well 19

Fort Carson geophysical program

47. At Fort Carson, the resistivity surveys were conducted by WES, and the refraction surveys were conducted by CSM. The resistivity and refraction surveys were not conducted in identical locations or orientations, as shown in Figure 9. Table 2 summarizes the surveys conducted at Fort Carson.

Table 2

Fort Carson, Colo., Geophysical Program

Survey Type	Performing Agency	Survey No.	Survey Line Length, ft	Comments
Refraction	CSM	1	1650	Significant topographic variation along line
		2	825	At same location as WES-4
		3	1100	Approximately perpendicular to WES-3
Resistivity	WES	1	1000	WES-1 and WES-2 are perpendicular, crossing at midpoints
		2	900	
		3	1000	
		4	1000	
		5	700	Line length limited by topography

Geophysical Survey Results

48. Seismic refraction data were processed using a computer graphics tablet to pick first-arrival events from the analog records at each geophone location. Arrival time-distance plots for each survey were automatically produced by a microcomputer-plotter system, straight-line segments were fit manually to the data, and then seismic velocities and interface depths were determined using techniques and computer programs described by Butler et al. (1982). Electrical resistivity field data were converted to apparent resistivity using Equation 1 and K_G for the Schlumberger array and sounding curves prepared for each survey (ρ_A versus L-spacing). The resistivity sounding curves were smoothed and corrected for lateral effects, and interpreted using the techniques described by Butler et al. (1982).

49. Figures 10-19 are the results of the seismic refraction and electrical resistivity surveys at the five locations at the White Sands, New Mexico, site. Results of surveys at the Fort Carson, Colorado, site are shown in Figures 20-27. Seismic velocities are shown by each line segment (inverse slope of the line segment) in the seismic refraction time-distance plots. The refraction plots also contain the calculated interface depths, indicated at the intersection points of two line segments. Except for the field data and smoothed, corrected sounding curves, no additional information is shown on the electrical resistivity plots. Interpretation of these data is discussed in Part V.
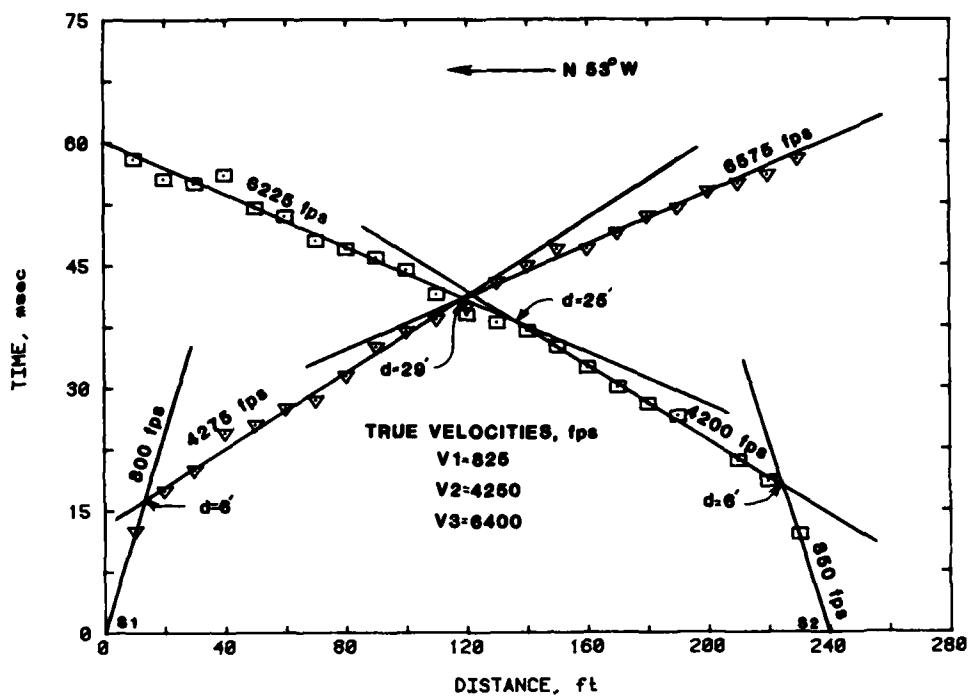
Figure 10. Seismic refraction data, HTA-1, White Sands
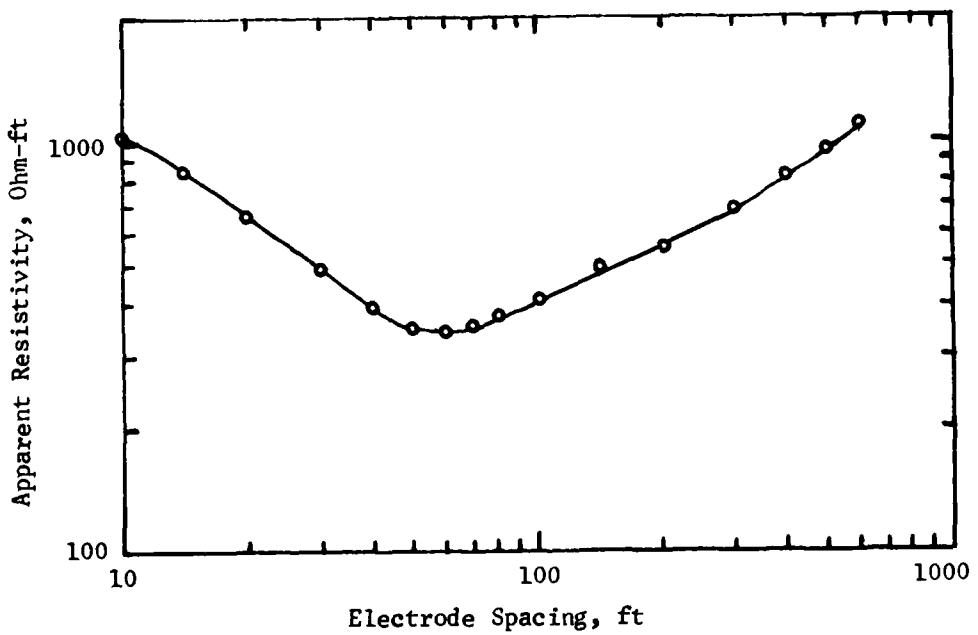
Figure 11. Electrical resistivity data, HTA-1, White Sands
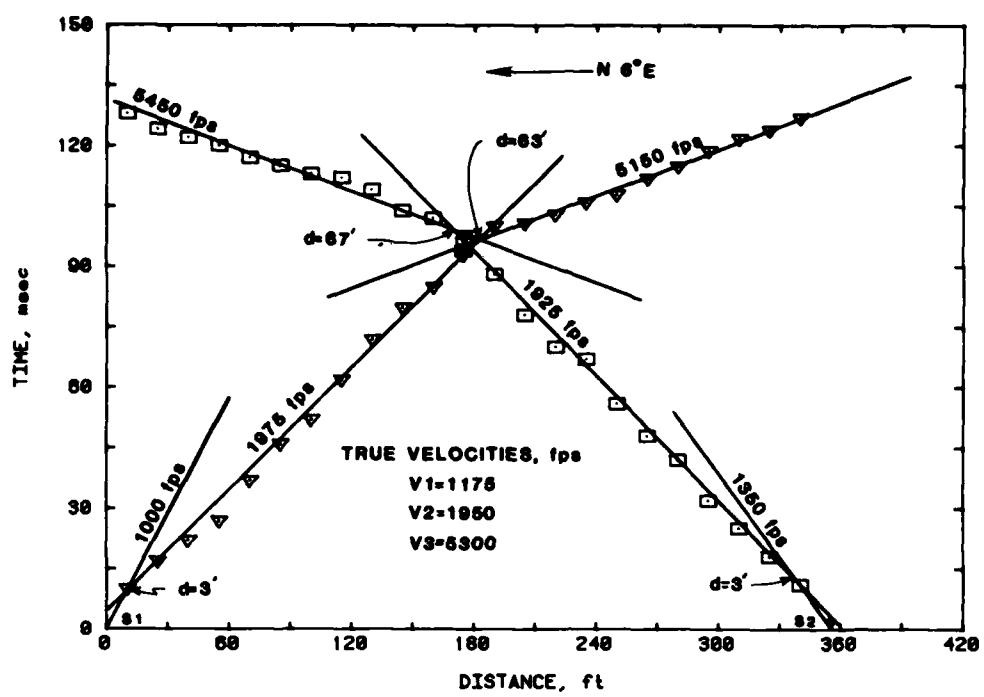
Figure 12. Refraction data, B-30, White Sands
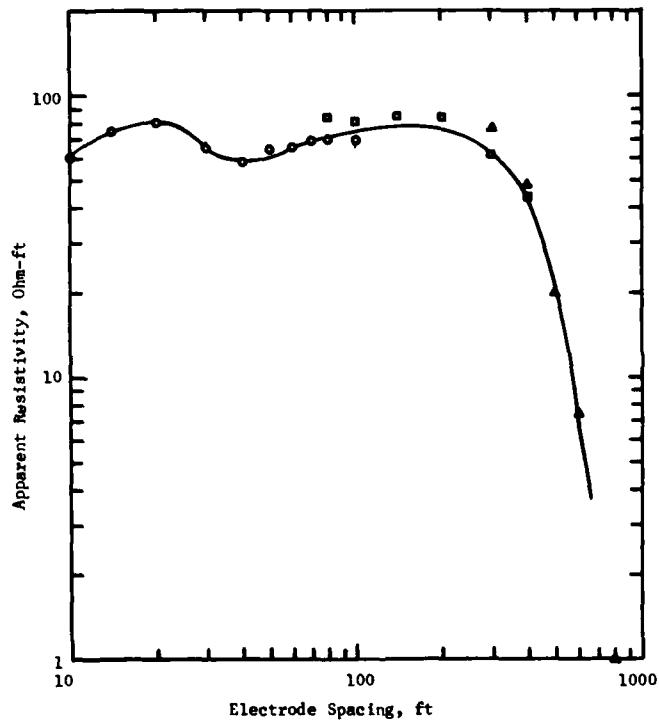
Figure 13. Electrical resistivity data, B-30, White Sands

32
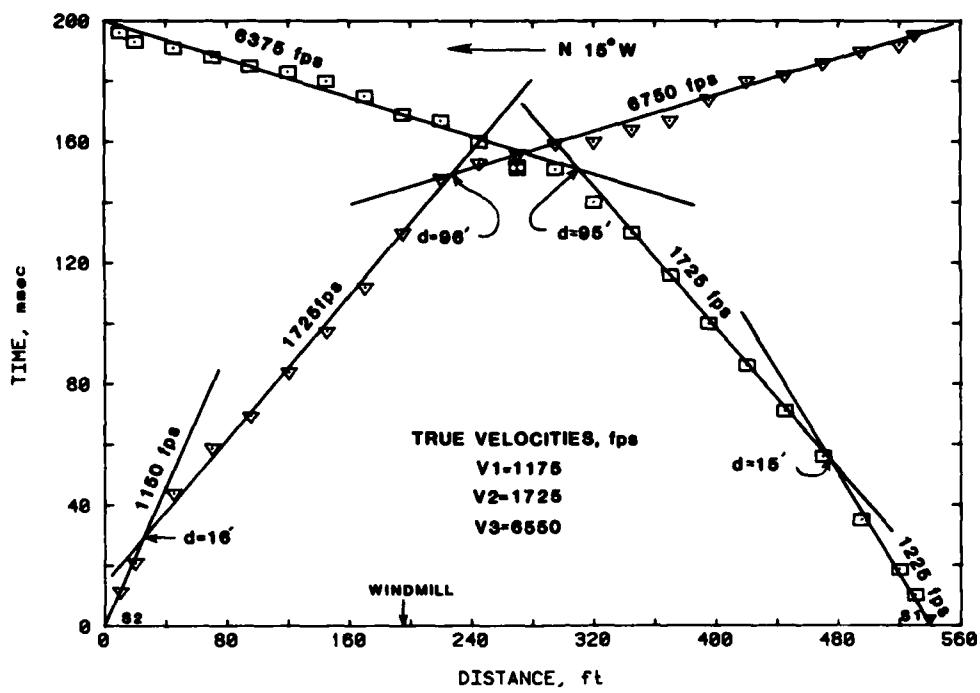
Figure 14. Seismic refraction data, T-14, White Sands
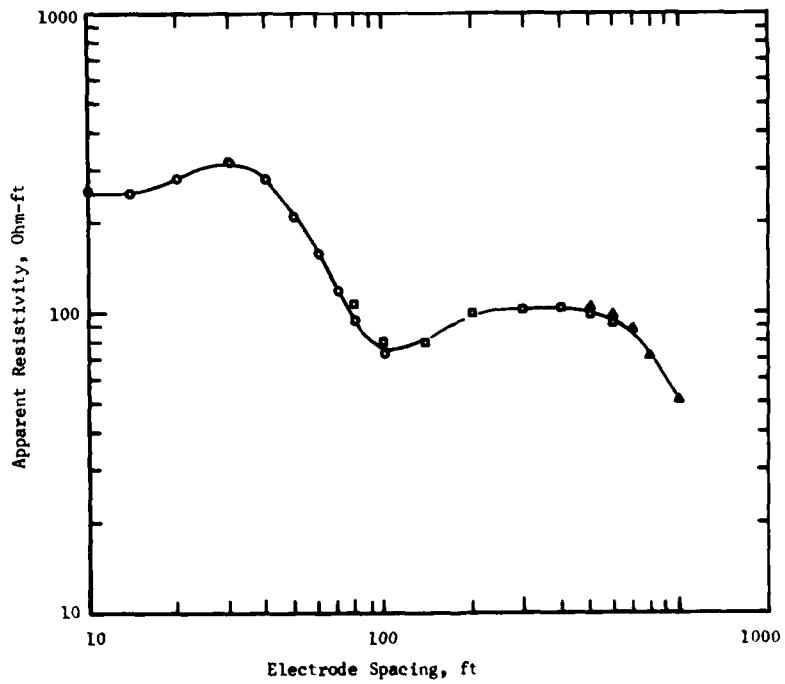
Figure 15. Electrical resistivity data, T-14, White Sands

33
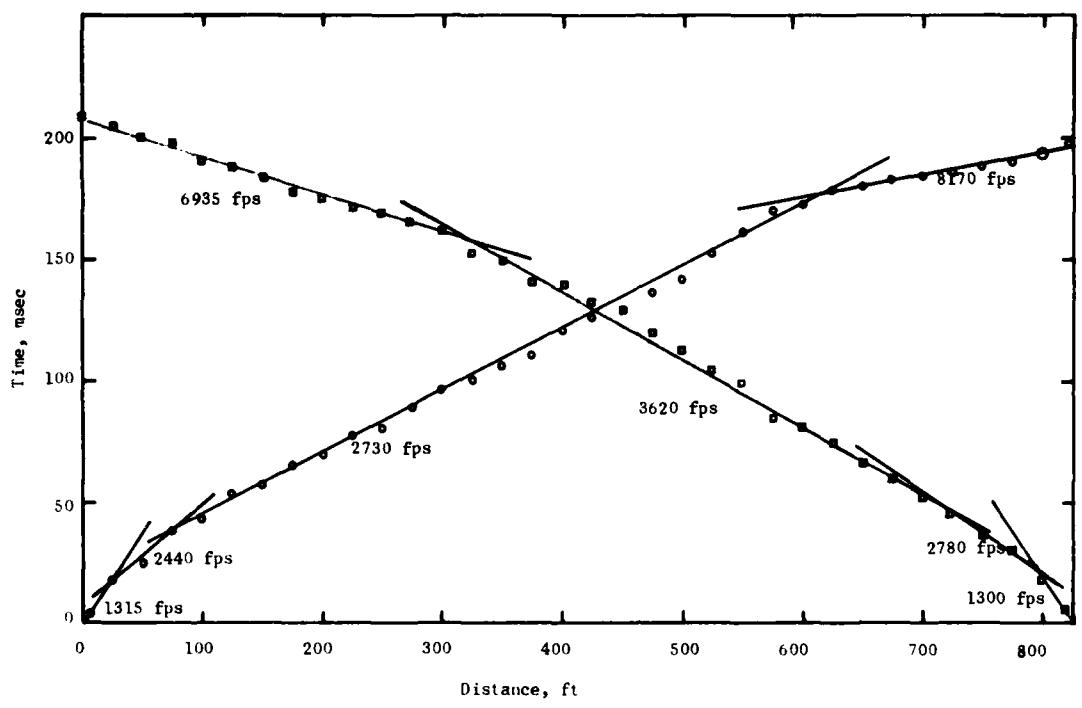
Figure 16. CSM refraction results, MAR, White Sands
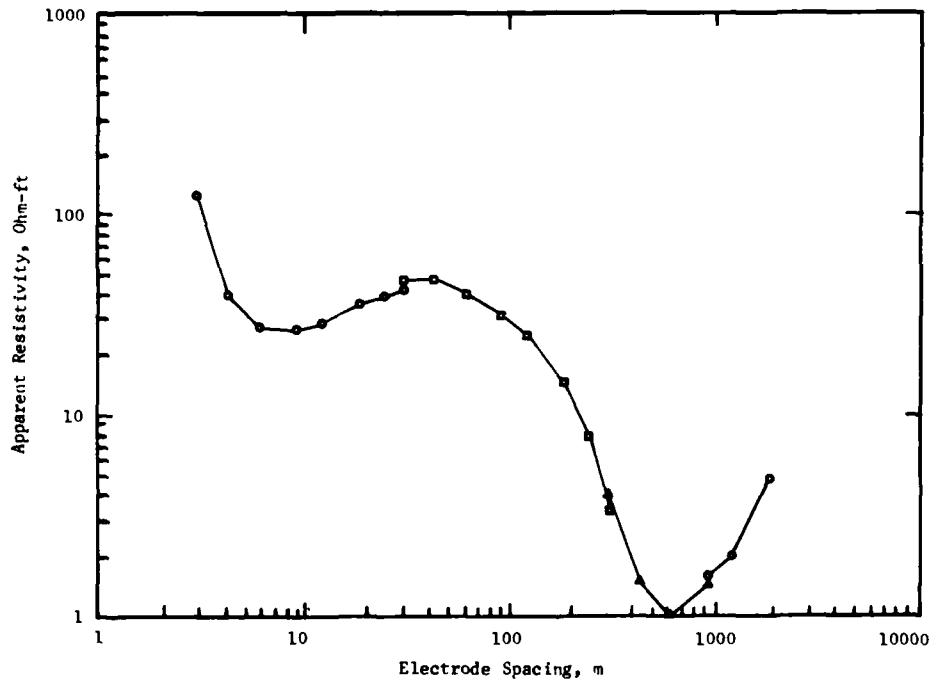
Figure 17. USGS resistivity data, MAR, White Sands

34
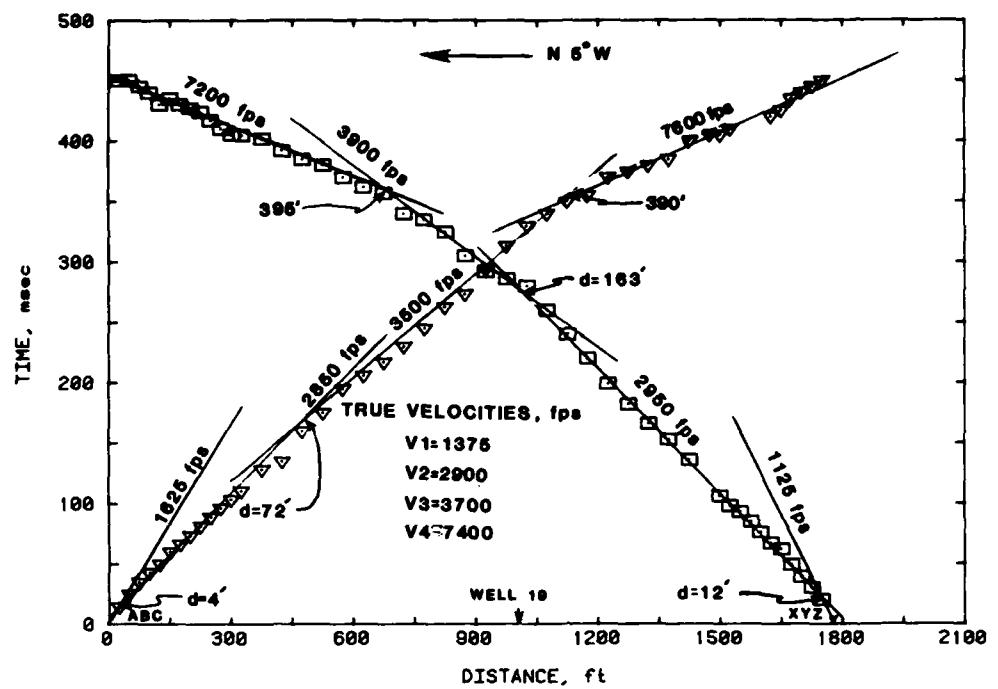
Figure 18. Seismic refraction results, SW-19, White Sands
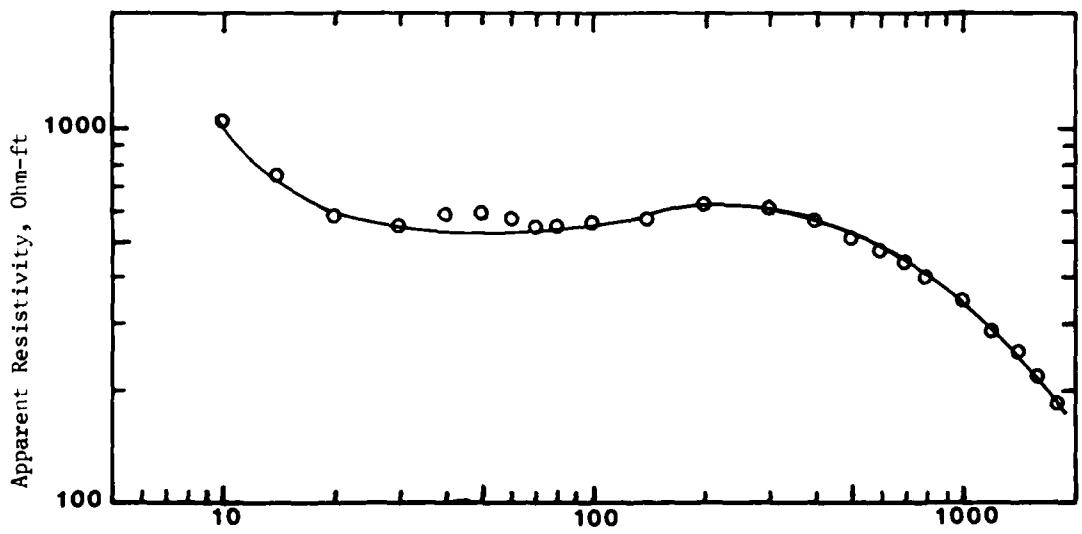
Figure 19. Electrical resistivity results, SW-19, White Sands

35
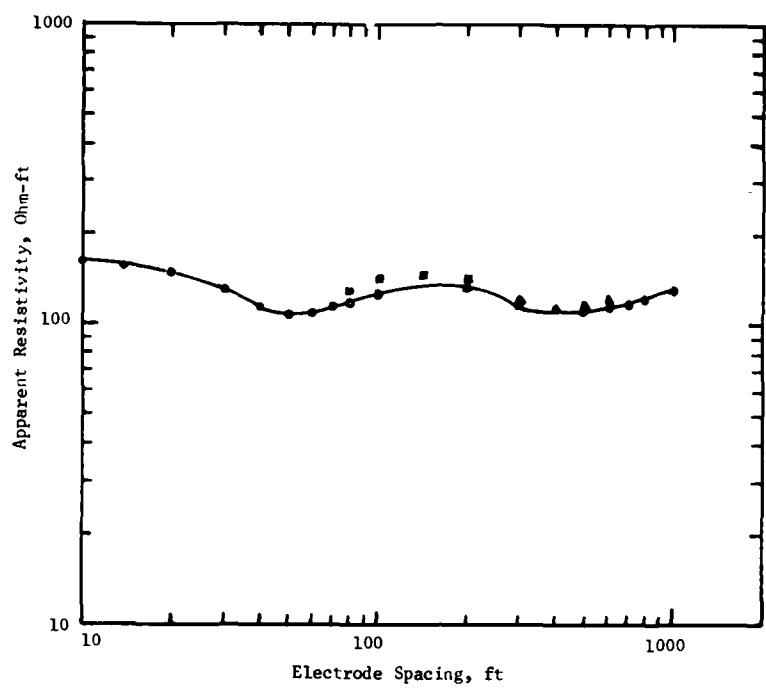
Figure 20. Electrical resistivity data, WES-1,
Fort Carson
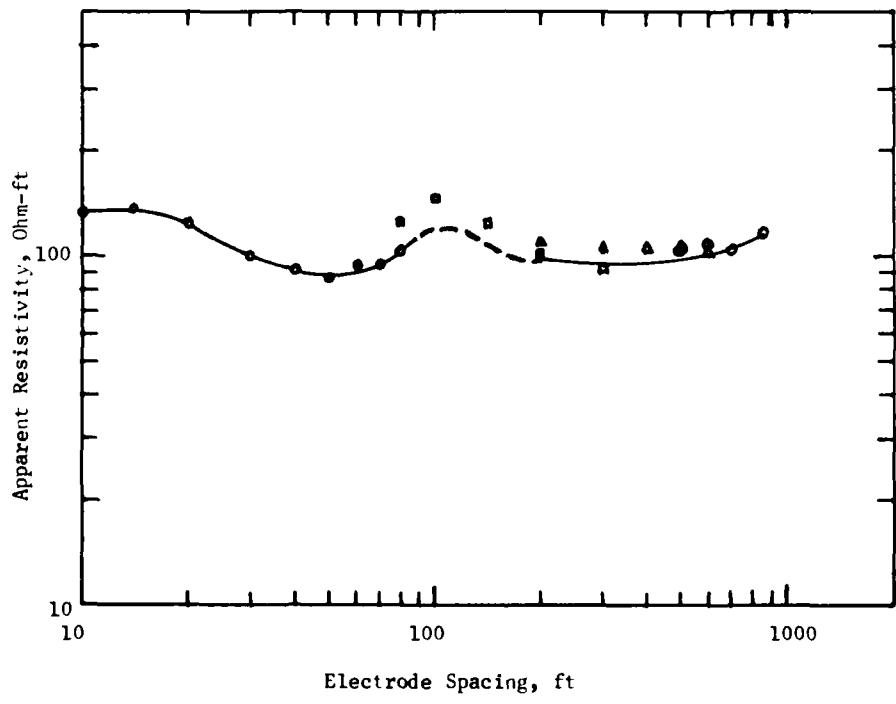
Figure 21. Electrical resistivity data, WES-2, Fort Carson

36
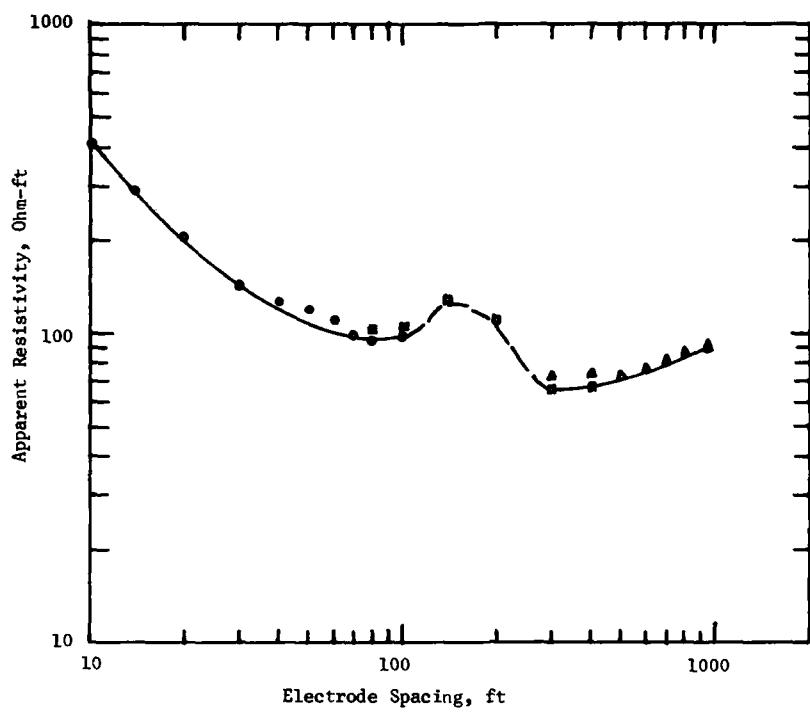
Figure 22. Electrical resistivity data,
WES-3, Fort Carson
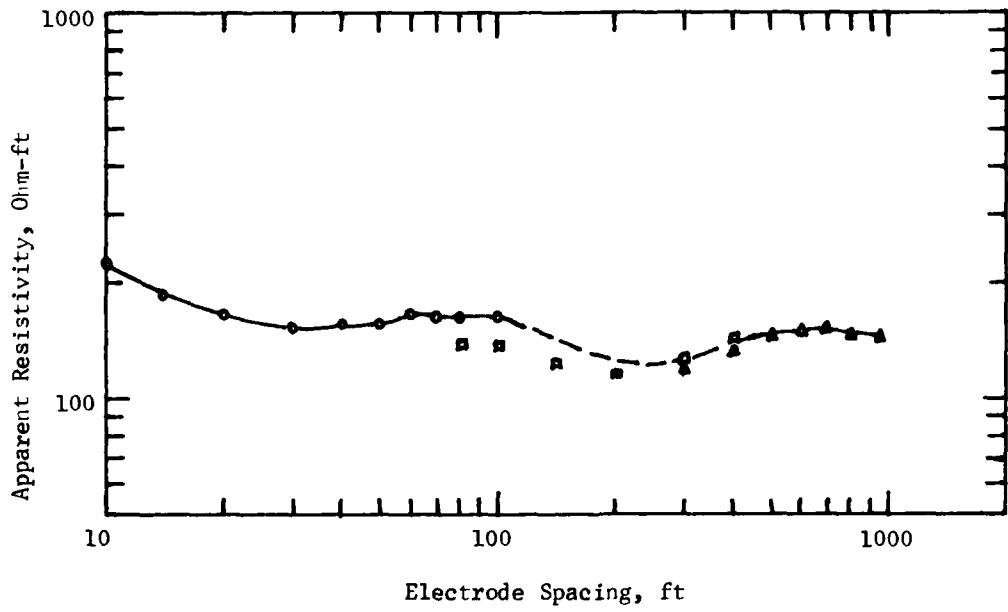
Figure 23. Electrical resistivity data, WES-4, Fort Carson
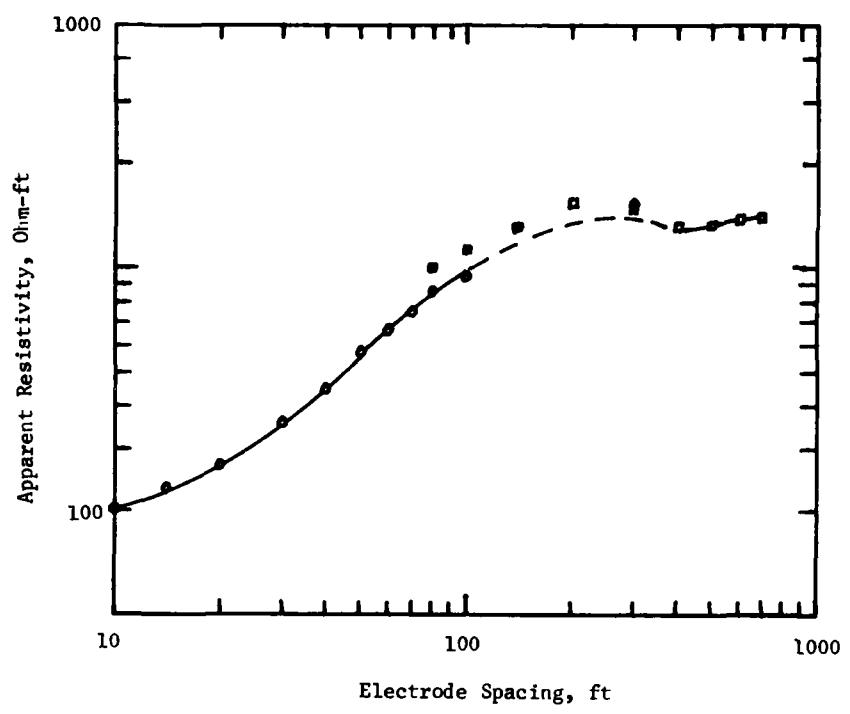
Figure 24. Electrical resistivity data, WES-5, Fort Carson
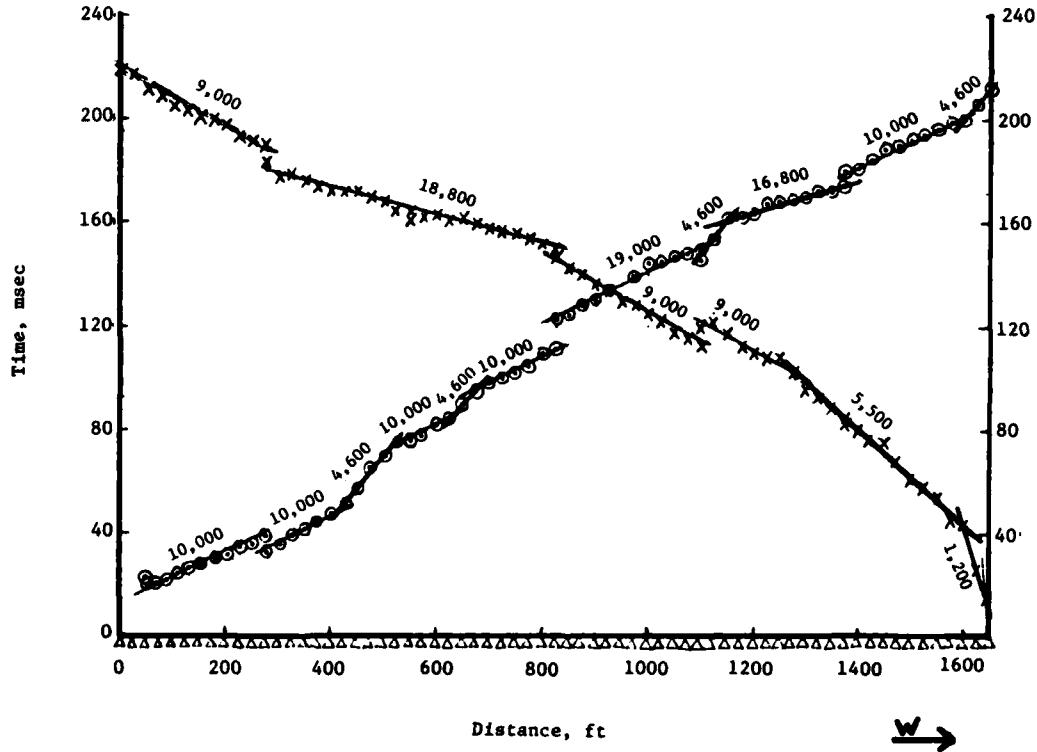
Figure 25. Seismic refraction data, CSM-1, Fort Carson
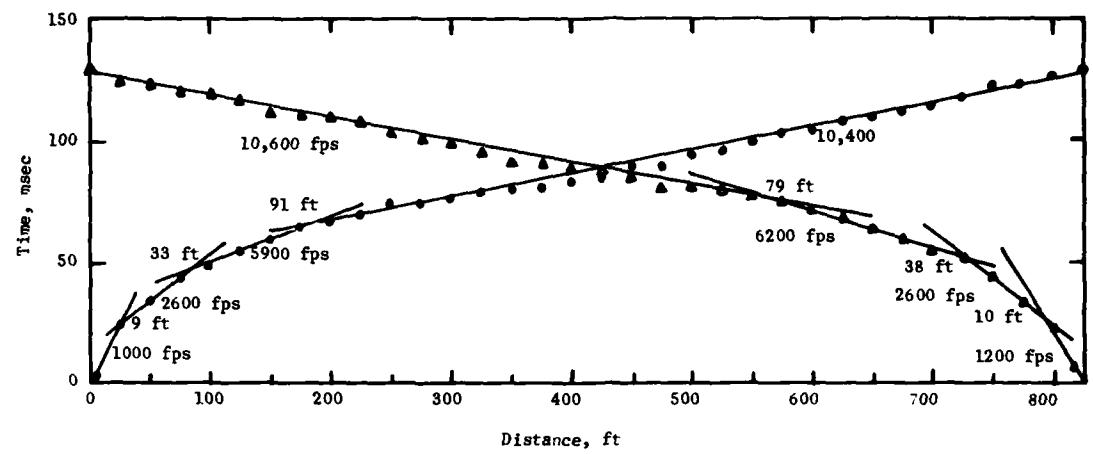
Figure 26.   Seismic refraction data, CSM-2, Fort Carson
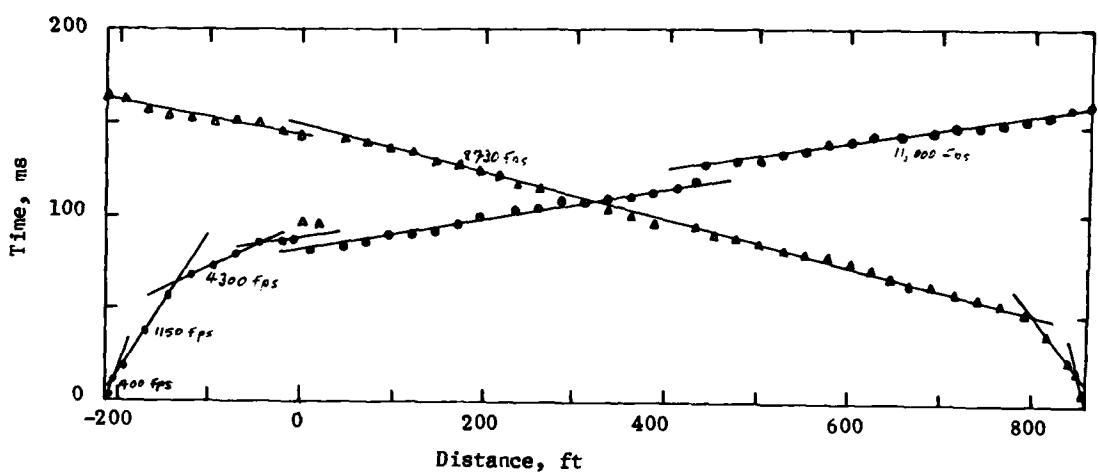
Figure 27.   Seismic refraction data, CSM-3, Fort Carson

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PART V: GEOPHYSICAL INTERPRETATION AND GEOLOGICAL CORRELATION

Geophysical Interpretation

50.   For the ground-water detection application of geophysics for
military use, the assessment of the presence of ground water must rely
primarily on the geophysical test results at a given surface location
(i.e., geological information is assumed to be either unavailable or, if
available, there is no one capable of interpreting it and integrating it
into the ground-water assessment) (see Part II).   Thus, the interpreta-
tions developed in this section are determined directly from the survey
data using standard procedures.   This type of interpretation can proceed
without any prior knowledge of subsurface conditions, although judgment
based on experience is desirable.   All of the interpreters were geo-
science professionals,* all had cursory knowledge of the geologic condi-
tions prior to the field surveys and the interpretation, but all were
careful not to make use of the prior knowledge in the standard interpre-
tation procedure.   In the geophysical ground-water assessments that
follow, a qualitative rating using the terms "poor," "fair," or "good"
is given indicating the confidence in the assessment for the site.

51.   Results of interpretation of the seismic refraction time-
distance plots were introduced in Part IV.   As an example of the proce-
dures by which the electrical resistivity survey data are interpreted,
the resistivity sounding at SW-19 at the White Sands site is examined.
Based on the sounding curve characteristics (Figure 19), a "first guess"
or trial model of the subsurface is deduced.   The minimum number of
layers in the trial model is indicated by the number of relative maxima
and minima in the sounding curve, but well-defined changes in slope of
the curve may suggest a model with more than the minimum number of
layers.

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*   Two of the interpreters have degrees in geophysics and one has a
    degree in geology.   The interpreters have practical experience in
    geophysical data processing and interpretation ranging from 1 year to
    more than 10 years.

52. The trial model is input, along with the field sounding data, to a resistivity interpretation computer program. The program adjusts the parameters of the trial model until a model sounding curve is produced which closely matches the field sounding curve. Interpretation of the sounding at SW-19 using the trial model, final model, and field sounding curves is illustrated in Figure 28. The final model curve fits the field curve within experimental accuracy. The initial and final resistivity models are compared in Figure 29.
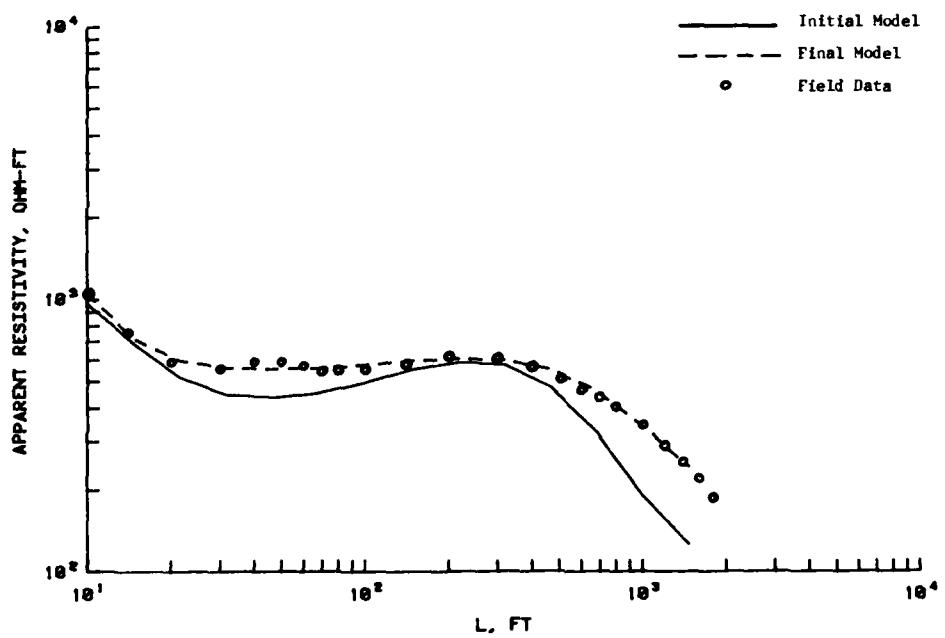
Figure 28. Example of resistivity interpretation procedure, SW-19, White Sands

Geophysical interpretation of White Sands survey data

53. HTA-1. Refraction and electrical resistivity data for the geophysical surveys at HTA-1 are shown in Figures 10 and 11, respectively. The refraction data indicate three subsurface layers. The resistivity data, however, are somewhat ambiguous. The sounding curve, Figure 11, indicates a minimum of three layers but suggests as many as five layers. Thus, the resistivity data were interpreted in terms of

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Initial Model	Final Model
ρ_1 = 1500 ohm-ft	ρ_1 = 2628 Ohm-ft
h_1 = 5 ft	h_1 = 3.4 ft
ρ_2 = 400	ρ_2 = 534
h_2 = 50	h_2 = 45.2
ρ_3 = 800	ρ_3 = 643
h_3 = 200	h_3 = 350.2
ρ_4 = 100	ρ_4 = 167

NOTE: ρ_i and h_i are the resistivity and
thickness, respectively, of the ith
layer of the model.

Figure 29.   Comparison of the initial and
final models for the resistivity inter-
pretation, SW-19 (see Figure 28)

three-, four-, and five-layer models. The three resistivity models and
the refraction model are compared in Figure 30, along with the inter-
preted results of the CSM refraction line.

54. The four- and five-layer resistivity models in Figure 30 for
HTA-1 agree closely in the top three resistivities and first two inter-
face depths. Also, the WES and CSM seismic refraction models agree
closely, although the somewhat longer CSM refraction line detects a
third interface at an interpreted depth of 105 ft. The first interface
depth in both the resistivity and refraction models agrees, and the
third interface location in the five-layer resistivity model and the CSM
refraction model agrees. However, the second interface in the refrac-
tion models is considerably shallower than the second interface in the
resistivity models.

55. Based on the complementary geophysical models in Figure 30
and the detection concepts of Part II, the following ground-water assess-
ment is made for location HTA-1:
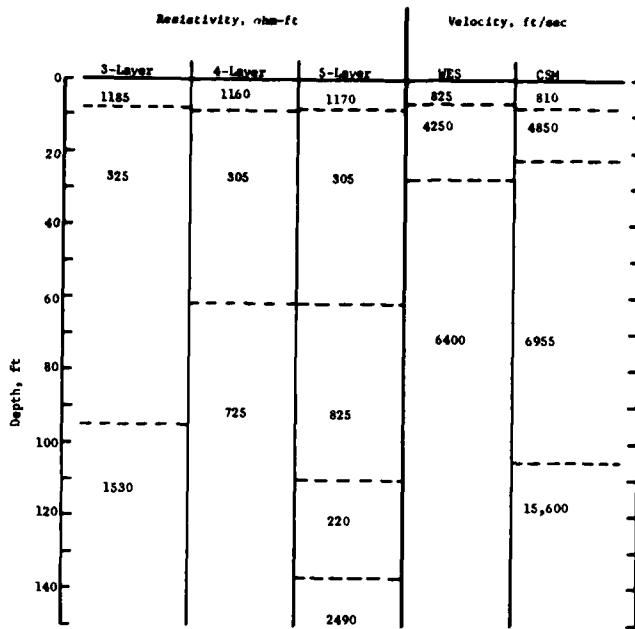
Figure 30. Geophysical models, HTA-1,
White Sands

a. If ground water is present in usable quantities, it will
be shallower than 105 ft, since the material below this
depth has a seismic velocity characteristic of dense,
low-porosity rock.

b. There are indications of a possible water table at the
approximate 8-ft depth, due to lower resistivity (305 ohm-
ft) and a seismic velocity (4250 ft/sec) close to the
characteristic 5000 ft/sec velocity below the first
interface.

c. If ground water is present at a depth of 8 ft, it must be
fresh since the bulk resistivity is high for an aquifer.

d. Since the seismic velocity is somewhat low and the resis-
tivity is high, the qualitative rating of the ground-water
assessment is "poor."

56. B-30. Refraction and resistivity data for the geophysical
surveys at this location are shown in Figures 12 and 13, respectively.
The seismic refraction results indicate a three-layer model, and the
material below the interface at 65-ft depth has a seismic velocity of
5300 ft/sec, very close to the characteristic 5000 ft/sec velocity of
shallow saturated sediments. Qualitatively, the resistivity sounding

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curve indicates apparently a five-layer model, with the lowest layer
detected having an extremely low resistivity (conductive basement for
the survey). Generally, such a conductive basement indicates a thick
zone of very saline ground water or a thick, conductive, clay layer.
Quantitatively, it is difficult to fit a model to the sounding curve
(see also comments in Appendix A). Also, the final resistivity sounding
curve is sensitive to the choice of trial models. The resistivity
model shown in Figure 31, with the refraction model, is an "average"
model based on eight final models (including some deduced from the Wenner
sounding); the vertical bars on the interface depths indicate the range
of depths predicted by all the models. The depth range is ± 20 percent
of the average model depths in all cases.
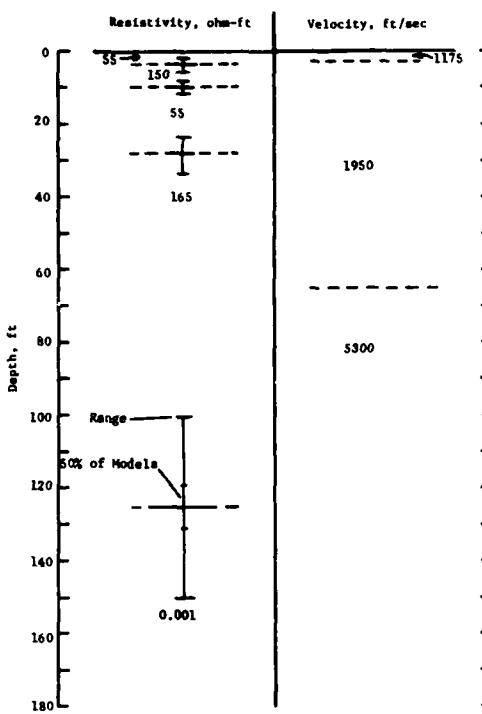
Figure 31. Geophysical models, B-30,
White Sands

57. Based on the complementary geophysical models shown in
Figure 31, the following groundwater assessment is made for location
B-30:

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     <u>a</u>.   There is a possible ground-water table at 65-ft depth,
           as indicated by the characteristic seismic velocity below
           this depth.

     <u>b</u>.   The ground water becomes very saline at 125-ft ($\pm$25 ft)
           depth.

     <u>c</u>.   Qualitative rating of this ground-water assessment is
           "good."

58. <u>T-14.</u> Refraction and resistivity data for the geophysical
surveys at location T-14 are shown in Figures 14 and 15, respectively.
The refraction data indicate a three-layer model. A large velocity
increase occurs at a depth of 95 ft (from 1725 to 6550 ft/sec); this
type of velocity increase is characteristic of the increase that occurs
at a water table, although the 6550 ft/sec velocity for the material
below 95 ft is larger than normally anticipated for this depth. Inter-
pretation of the resistivity data is complicated by the apparent occur-
rence of a thin, very low-resistivity layer at a depth of ~16 ft. Known
as a highly equivalent layer, this very low-resistivity layer makes it
difficult to interpret depths to interfaces below it. Figure 32 pre-
sents resistivity and refraction models for T-14.

59. Based on the complementary geophysical models in Figure 32,
the following ground-water assessment is made for location T-14:

     <u>a</u>.   There is a possible ground-water table at 95-ft depth,
           as indicated by a large seismic velocity contrast at an
           interface at that depth.

     <u>b</u>.   Below a depth of ~150 ft, the ground water becomes saline.

     <u>c</u>.   Qualitative rating of this ground-water assessment is
           "fair."

60. <u>MAR.</u> Refraction and resistivity data for the geophysical
surveys at location MAR are shown in Figures 16 and 17, respectively.
The resistivity sounding location was about 0.5 mile east of the refrac-
tion survey location, so resistivity and refraction models cannot be
compared directly. Figure 33 presents the refraction model and the re-
sistivity model for the displaced resistivity sounding location. Using
the resistivity data shown in Figure 17 as well as data from a sounding
0.5 mile west of the refraction location, the resistivity interface at
245 ft in Figure 33 projects to a depth of ~300 ft beneath the refraction

45
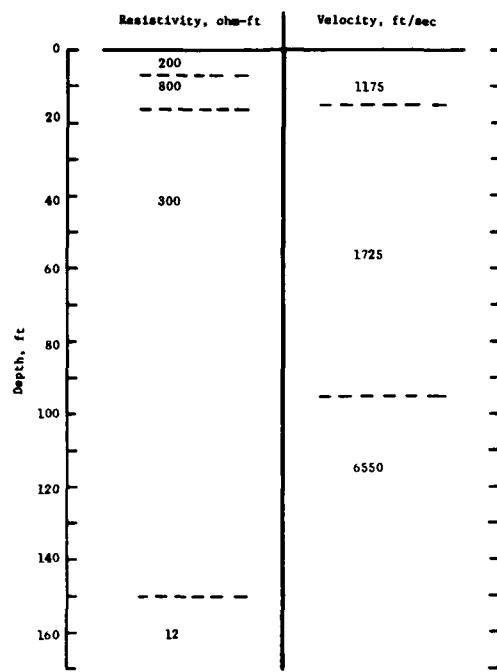
Figure 32.   Geophysical models,
T-14, White Sands
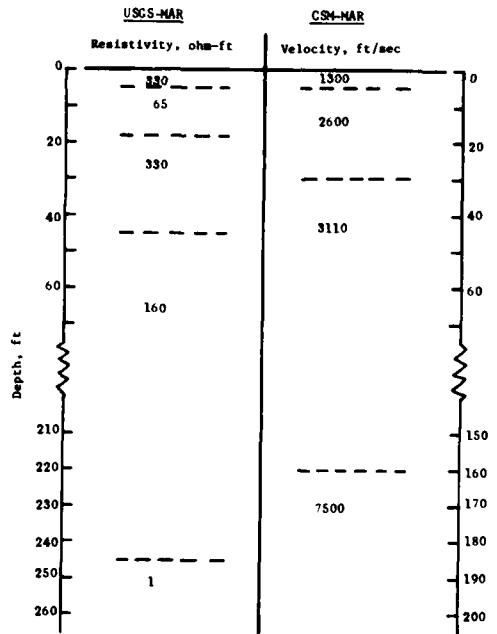
Figure 33.   Geophysical models
based on USGS and CSM data,
MAR, White Sands

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survey location. The large velocity contrast at 160-ft depth (increase from 3110 to 7500 ft/sec) is characteristic of the occurrence of a water table, although a velocity of 7500 ft/sec could also be indicative of a poorly cemented or weathered rock. There is, however, no indication of a major resistivity change at this depth.

61. Based on the geophysical models in Figure 33, the following ground-water assessment is made for location MAR:

a. If ground water is present in usable quantities, it will be shallower than ~1000 ft, since the resistivity interpretation indicates a resistive basement at that depth, i.e., a dense, low-porosity rock (not shown in Figure 33).

b. The seismic data indicate a possible water table at 160-ft depth.

c. Groundwater between ~300 ft and the resistance basement is very saline, or a very thick clay layer exists.

d. Qualitative rating of this ground-water assessment and the ground-water potential is "fair."

62. SW-19. Refraction and resistivity data for the geophysical surveys at SW-19 are shown in Figures 18 and 19; the interpretation procedure for the resistivity data is illustrated in Figures 28 and 29. Both the refraction and resistivity data indicate a four-layer model, as shown in Figure 34 (a model based on the CSM data for this location is also shown).

63. The geophysical data for this location are straightforward to interpret and follow a familiar pattern for sites where a water table occurs in coarse-grained sediments. A geological interpretation of the geophysical models is also shown in Figure 34. The following ground-water assessment for SW-19 can be made:

a. A ground-water table occurs at a depth of 400 ft.

b. Based on the interpreted resistivity beneath 400 ft, the ground water is fresh.

c. Qualitative rating of this groundwater assessment is "very good."

Geophysical interpretation
of Fort Carson survey data

64. Geological and topographical complexities at the Fort Carson site combined to make a straightforward geophysical interpretation of

47
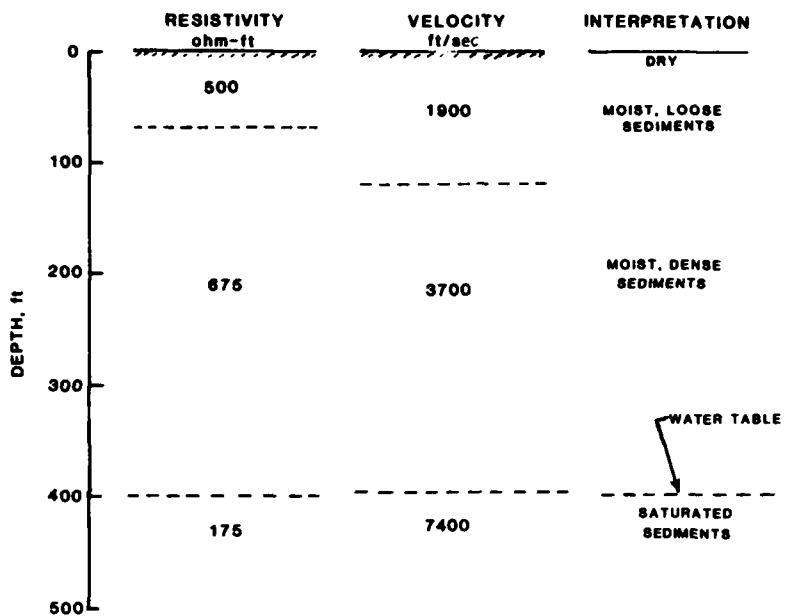
Figure 34. Geophysical models and interpretation,
SW-19, White Sands

all the data impossible (see also comments in Appendix A). Also, except
for WES-4 and CSM-2, the refraction and resistivity surveys were not
conducted at the same locations. Thus, the geophysical interpretation
will concentrate on WES-4 and CSM-2.

65. Figure 35 presents geophysical models for WES-4 and CSM-2
(same location). Interfaces at depths of approximately 35 and 100 ft
are predicted in both models. Based on the geophysical models in
Figure 35, the following ground-water assessment can be made:

a. There is a possible water table at a depth of ~35 ft,
indicated by a velocity increase from 2600 to 6050 ft/sec,
although this could be an interface between soil and rock
since the resistivity increases at this depth.

b. If there is ground water present below 35 ft, it becomes
somewhat brackish at ~60 ft, since there is a significant
resistivity decrease at that depth.

c. There is somewhat less ground-water potential below
100 ft, since the velocity and resistivity indicate a
lower porosity rock below that depth.

d. Qualitative rating of this ground-water assessment is
"poor."

48
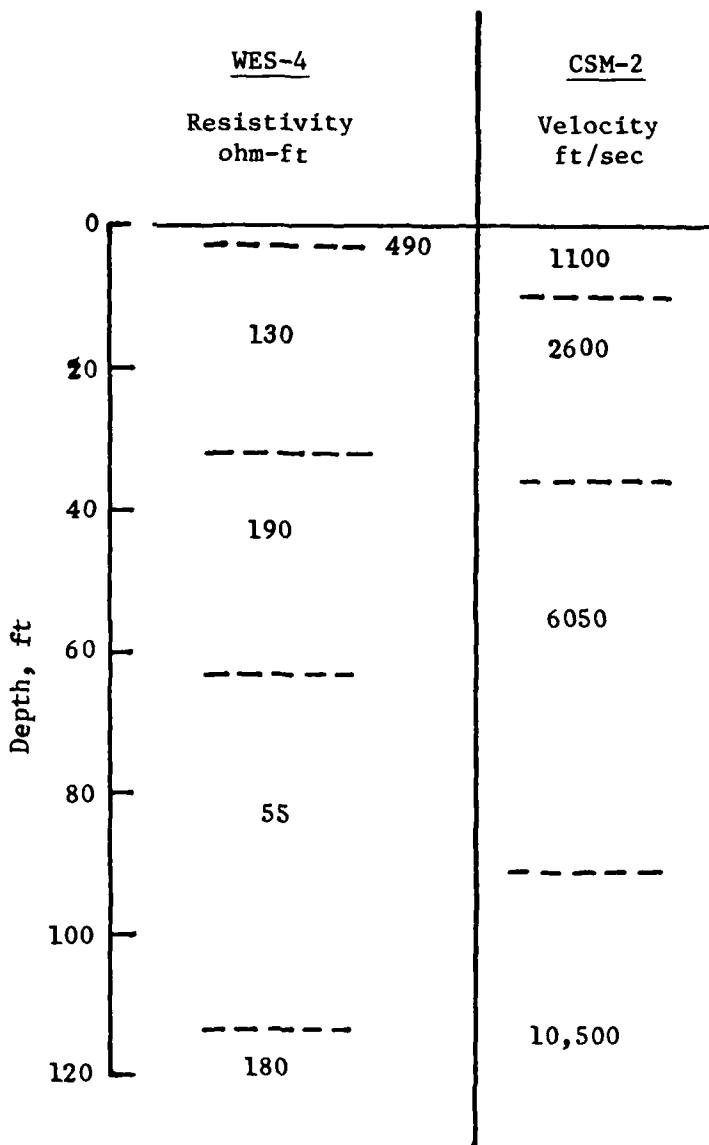
Figure 35.   Geophysical models, Fort Carson

Conceivably, the procedures used to make the preceding ground-water
assessments can be cast in the form of a flowchart and computer algorithm
for use by nonprofessionals.

49

Geological Correlation and Constraint
of Geophysical Interpretations

66. The preceding discussion and ground-water assessments have not involved any considerations of specifics of the sites* or existing knowledge of geological and ground-water conditions at the sites. Generally, all available knowledge about a site is used to constrain or guide the geophysical interpretation. In an effort to evaluate the effectiveness of the preceding ground-water assessments made under the detection application constraint, all available ground-water and other geologic information will now be compared to the geophysical models interpreted from the survey data. The extent of information available at each location varies considerably. Available information could include such elements as (a) water table depth at nearby borehole only, (b) regional geologic information plus specific information at a borehole, which must be extrapolated to actual survey location, (c) water table depth plus general information on material type at nearby borehole, or (d) detailed borehole log information at the survey location.

Geological verification
of White Sands geophysical
ground-water assessments

67. Results of the five geophysical ground-water assessments made for the White Sands locations are summarized in Table 3. The available ground-water and geologic information for the five locations is summarized in Table 4. Comparison of Tables 3 and 4 indicates general qualitative agreement between the geophysical ground-water assessments and known ground-water data for all of the locations except HTA-1. The predicted water table depths are consistently too shallow, however, compared to the borehole water depth measurements, by amounts ranging from

---

* An exception to this is the Fort Carson site, where topographic variations and lateral complexities of the geology apparently make a straightforward interpretation of some of the geophysical data impossible.

Table 3

Summary of White Sands Geophysical Ground-water Assessments

Location	Predicted Water Table Depth, ft	Water Quality Statement	Predicted Aquifer Thickness	Confidence in Ground-Water Assessment
HTA-1	8	Fresh	100 ft	Poor
B-30	65	Fresh from 65-125 ft, becoming very saline below 125 ft	?	Fair to good
T-14	95	Fresh from 95-150 ft, becoming saline below 150 ft	?	Poor to fair
MAR	160	Fresh from 160-300 ft; very saline from 300-1000 ft	Base of aquifer, 1000 ft	Fair
SW-19	400	Fresh	?	Very good

12 percent at SW-19 to 28 percent at B-30 and T-14 (not considering HTA-1).* The water table depth comparisons are given in Table 5. The water quality assessments in Table 3 are generally consistent with the water quality measurements reported in Table 4.

68. HTA-1. No explanation for underpredicting actual water table depth suffices for HTA-1. An alternate explanation for the interface at 8 ft, which appears on both refraction and resistivity interpretations, is not apparent. The interface at 62 ft in the resistivity model (Figure 30) is at the right depth to correspond to the water table, but the resistivity actually increases from 305 to 825 ohm-ft at this interface. Neither geophysical model indicates an interface at the 82-ft depth where weathered granite was reported. The borehole geophysical logs (neutron and natural gamma) do not show prominent water table indications at 65 ft, although both logs exhibit dramatic changes at ~84 ft. The

* Conversely, the predicted water table depths would have to be increased by amounts ranging from 14 percent for SW-19 to 39 percent for T-14 to agree with the measured depths.

51

Table 4

Summary of Geologic/Ground-Water Information

For White Sands Test Locations

Location	Measured Water Table Depth, ft/ Date	Variation ft	Water Quality* (Resistivity) ohm-ft	Type Geologic Information Available and Summary	Comments
HTA-1	64 (2/15/83)	6	50 fresh	Limited borehole lith-ology info. Sand and gravel to 82 ft. Weathered granite encountered at 82 ft.	Natural gamma and neutron borehole geophysical logs
B-30	89.5 (2/15/83)	1	<4 (@185 ft) saline	None	Natural gamma and neutron borehole geophysical logs
T-14	132 (2/16/83)	1	21 (@200 ft) 22 (@300 ft) marginal	Borehole lithology log for entire 6000-ft depth. Sand with silt and clay, 0-105 ft; clay with sand and silty, 105-220 ft; sand with clay, 120-180 ft; clay with sand and silt, 180-430 ft.	Complete set of borehole geophysi-cal logs from 400-6000 ft

(Continued)

* Generally fresh water is considered to have <1000 mg/ℓ total dissolved solids. This criterion converts approximately to a "specific conductance" <1560 μmhos/cm or a resistivity >21 ohm-ft.

Table 4 (Concluded)

Location	Measured Water Table Depth, ft/ Date	Variation ft	Water Quality* (Resistivity) ohm-ft	Type Geologic Information Available and Summary	Comments
MAR	214 (MAR-2; 2/14/83) 220 (MAR-2; 1981)	1	32 (~300 ft) 0.6 (@750 ft in MAR-2 and MAR-3) fresh (@300 ft)	Borehole lithology log. Gravel, 0-112 ft; clay, 112-160 ft; gravel, 160-165; clay, 165-200; gravel, 200-210; clay, 210-225; etc., predominantly clay below 630 ft.	Electric logs available
SW-19	454 (2/25/83) (427 for SW-18) (514 for SW-20)	5	85 (>400 ft) fresh	Limited material descriptions. Poorly sorted sands and gravels to >900 ft.	Nonpumping water level: 409 ft (7/22/64) (402 ft, SW-18; 462 ft, SW-20)

Table 5

Comparison of Predicted and Measured

Water Table Depths

Location	Predicted Depth, ft D_p	Measured Depth, ft D_m	% Error $\dfrac{D_m - D_p}{D_m} \times 100$	Required % Increase in D_p $\left\lvert\dfrac{D_p - D_m}{D_p}\right\rvert \times 100$
HTA-1*	8*	64.0	88*	700*
B-30	65	89.5	27	38
T-14	95	132.0	28	39
MAR	160	214.0	25	34
SW-19	400	454.0	12	14

* Discussion of error for the HTA-1 case is not meaningful since the water table was not detected by the complementary geophysical methods.

natural gamma log shows a decrease in activity at 110 ft, which would correlate with an interpretation of the velocity interface at 110 ft being the approximate boundary between weathered and unweathered granite.

69. SW-19. Geologic conditions at SW-19, primarily coarse-grained sediments, are the most favorable for successful application of the ground-water detection techniques. As a consequence, geophysical ground-water assessment at SW-19 was the most successful of the five conducted at White Sands.

70. B-30, T-14, and MAR. Geophysical models for these locations are similar in that, apparently, saline water exists beneath the fresh water. The resistivity method is successful at detecting the freshwater-saltwater interface or transition zone. Also, there are considerable amounts of clay at these three locations, which complicates the ground-water assessments. Although the ground water is interpreted to be saline at depth at T-14 and MAR, the large resistivity decrease at large electrode spacings may be due to thick clay sequences at these locations.

Geological verification
of Fort Carson
geophysical ground-water assessment

71. Figure 36 presents a simplified lithology log for the well at
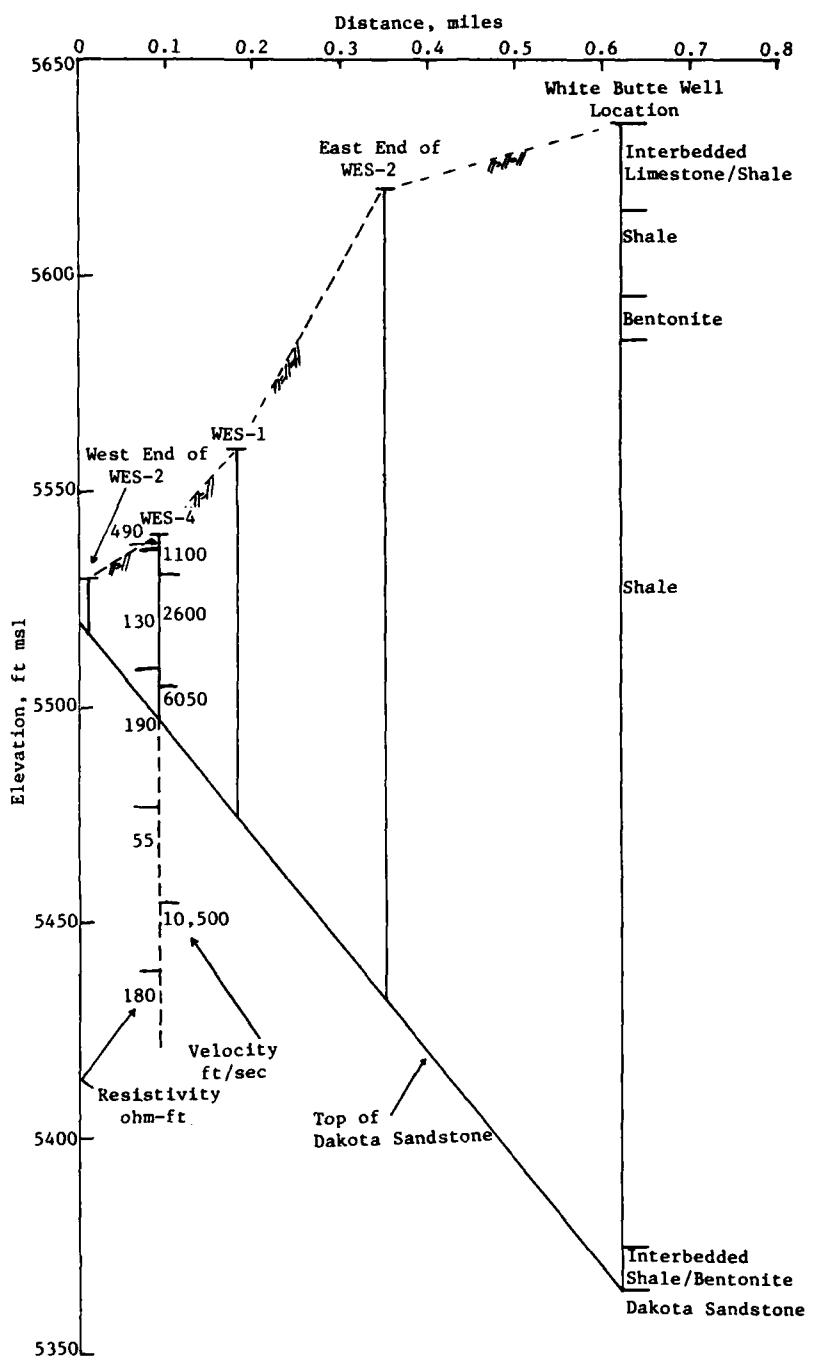
Figure 36. Cross section of Fort Carson site,
showing surface topography, top of the Dakota
Sandstone, survey line locations, White Butte
well borehole log, and WES-4/CSM-2 geophysical
models

White Butte. Also, the surface topography and top of the Dakota Sandstone are projected to the location of WES-4 and CSM-2. The surface topography is estimated from a 20-ft contour interval topographic map, and surface elevations are probably accurate to ± 5 ft. The top of the Dakota Sandstone is projected based on the known depth at the White Butte well and a regional value of dip for the Dakota Sandstone. The depth to the top of the Dakota Sandstone at the location of WES-4 and CSM-2 is probably accurate to only ± 15 ft.

72. The interface at 35 ft in the geophysical models (Figure 35) correlates with the top of the Dakota Sandstone, and the interface at 100 ft could correspond to the base of the sandstone unit. Two possibilities can be suggested for the resistivity interface at ~60-ft depth: (a) since the resistivity decreases, a change in ground-water salinity could occur at this depth; (b) since this location is very near the Dakota Sandstone outcrop, hence the area of recharge, this interface could be an unconfined water surface in the dipping aquifer.

73. In the geophysical ground-water assessment, the water table was interpreted based solely on the large velocity contrast; the velocity 6050 ft/sec occurring at such a shallow depth (35 ft) suggests the possibility of rock below 35 ft. The low resistivities (190 and 55 ohm-ft) between 35 and 100 ft suggest that if the unit is rock, then it is saturated, particularly the lower part. However, based solely on the geophysical data at one location, it is not possible to predict whether the interface is rock, saturated rock, or an unconfined water table.

56

PART VI: CONCLUSIONS AND RECOMMENDATIONS

74. This report presents the results of geophysical surveys at
two sites. The surveys, consisting of complementary seismic refraction
and electrical resistivity surveys, were conducted to assess the feasi-
bility of using two currently fieldable methods for military ground-
water detection applications (see Part II). Locations surveyed at the
two sites presented varied geological complexity and ground-water con-
ditions. Results of the surveys demonstrated success, marginal success,
and failure in the ground-water detection application.

Conclusions

75. Based on the results of this work, the following conclusions
are made regarding the applicability of the two complementary geophy-
sical methods for ground-water detection:

 a. For cases in which the water table occurs in coarse-
    grained sediments (sands and gravels), the geophysical
    methods can be used very successfully for ground-water
    detection.

 b. For cases in which the water table occurs in fine-
    grained sediments (clayey sands, silts, silty clays,
    sandy clays, etc.), the geophysical methods can be used
    for ground-water detection; however, the interpretation
    will sometimes not be as straightforward as for case a,
    and the difference between predicted and actual water
    table depth can sometimes be much greater than for case a.

 c. A freshwater-saltwater interface is easily detected by
    the resistivity method, but will not show as an interface
    in seismic refraction results; detection of this inter-
    face is useful in that any fresh water present will be
    shallower than the interface depth.

 d. Rock aquifers can be detected by the geophysical methods,
    but there may be nothing in the survey results to differ-
    entiate a rock aquifer from an unsaturated rock unit
    (except for the case where the rock unit has high resis-
    tivity, in which case the unit is not an aquifer).

 e. For some field situations, such as at the Fort Carson
    site, topographic variations and complex, lateral geo-
    logic changes make a straightforward data interpretation
    impossible.

57

<u>f</u>. In some cases, such as the HTA-1 location at White Sands, the straightforward interpretation method can lead to false identification of the water table.

<u>g</u>. In order to be conservative, geophysical water table depth estimates should be increased by ~40 percent.

<u>h</u>. It is envisioned that the desired depth of investigation will probably be dictated by considerations such as maximum desired drilling depth or maximum probable depth to water in an area; geophysical ground-water assessment productivity is strongly dependent on depth of investigation, as shown below:

Maximum Depth of Investigation ft	Estimated Number of Complete Geophysical Ground-Water Assessments per Day, 3-Man Crew
30	5-6
100	3-4
600	1-2
>600	1

76. The conclusions of the study can be summarized as follows: complementary seismic refraction and electrical resistivity surveys (a) can generally be used successfully for ground-water detection when the water table occurs in unconsolidated sediments, and (b) can generally not be used successfully for detection of ground water in confined rock aquifers. For the case of rock aquifers, a ground-water exploration program is required.

Recommendations

Equipment

77. Rugged, reliable seismic refraction and electrical resistivity instrumentation equipment that is commercially available would require very few modifications for military ground-water detection applications. The primary equipment development needs are for improved, more efficient cable and reel systems coupled with procedures for "putting out" and "taking up" cable from moving vehicles. The improved cable and reel systems could reduce the time required for conducting resistivity and refraction surveys by 25 to 50 percent.

58

Data processing and interpretation

78. Rugged field microcomputer systems that are commercially available would be suitable for processing and aiding in the interpretation of survey data. Also, interactive, user-friendly computer programs are available for survey data interpretation. The work required to convert computer programs to run on a specific microcomputer would be minimal.

Field personnel

79. Military personnel can be trained to conduct seismic refraction and electrical resistivity surveys. Minimum recommended training time is 3 months. While troops could be trained to make ground-water interpretations using a flowchart approach (or computer program based on the flowchart) incorporating the logic stated in this report and used for the ground-water assessments, this is not considered the most feasible approach. Feasible options for deployment are considered below.

Feasible deployment options

80. If the decision is made to develop a geophysical ground-water detection/exploration capability in field military forces, the following options are considered feasible:

   a. Recruit or assign junior officers with degrees in geology, geophysics, or other science/engineering fields with strong geoscience backgrounds to teams trained as specified in paragraph 79.

   b. Utilize teams trained as specified in paragraph 79 to conduct surveys and then relay data to a rear area interpretation unit or data analysis contractor that could handle data from several survey units and be better able to incorporate information from ground-water maps and databases into the ground-water assessments.

   c. Develop geophysical survey expertise in National Guard or Reserve units which already have identified professional geoscience expertise.

   d. Establish arrangements with Government agencies and/or geophysical firms for on-call geophysical testing and interpretation services for areas that are reasonably secure; these personnel should have full access to ground-water maps and databases.

59

Future work

81. The following requirements for future work are identified:

a. Develop improved cable and reel systems for fieldwork as identified above.

b. Adapt computer interpretation programs to run on selected field microcomputer systems.

c. Develop a geological and geophysical database for world areas of interest.

d. Proceed with research and development on state-of-the-art and emerging geophysical techniques for ground-water detection, such as frequency-domain and time-domain electromagnetic methods and the concept of determining the ratio of compression wave to shear wave seismic velocities as a function of depth.

e. Develop training manuals and programs for geophysical survey operators and for geophysical ground-water inter- pretation procedures; examine feasibility of developing geophysical ground-water interpretation "flowcharts," and ultimately an automated system for assessing ground- water potential.

f. Develop a totally integrated system for ground-water assessment that would incorporate (1) existing water resources-related information, (2) remote imagery analy- sis and interpretation capabilities, and (3) geophysical expertise.

60

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SCALES

```
1   0    1    2    3    4    5    6    7    8    9   10 MI

1  0  1  2  3  4  5  6  7  8  9  10 11 12 13 14  15  16 KM

6 4 2 0      6    12    18    24    30    36    42    48   54 THOU. FT
```

CONTOUR INTERVAL 500 AND 1000 FT

PLATE 1

White Butte
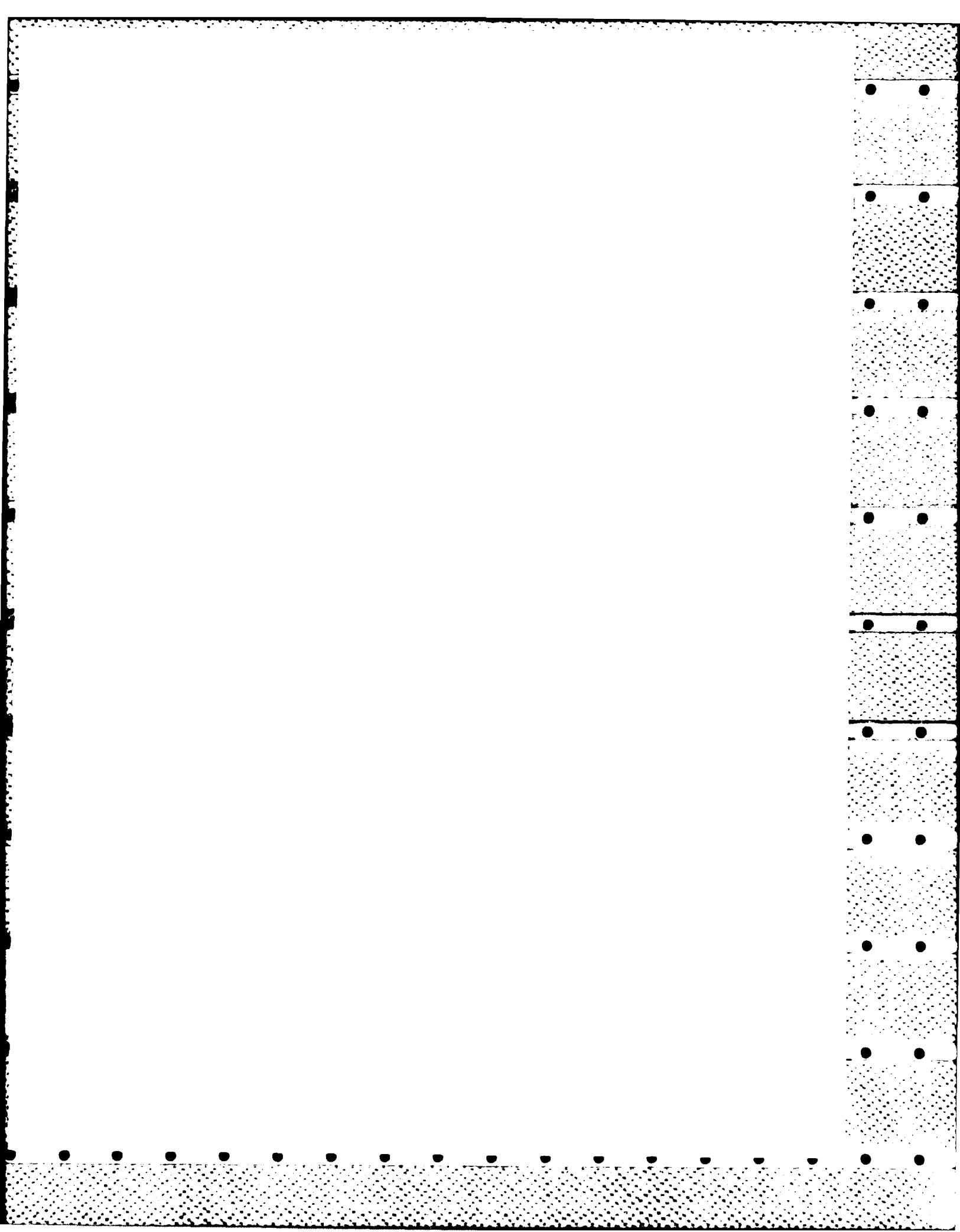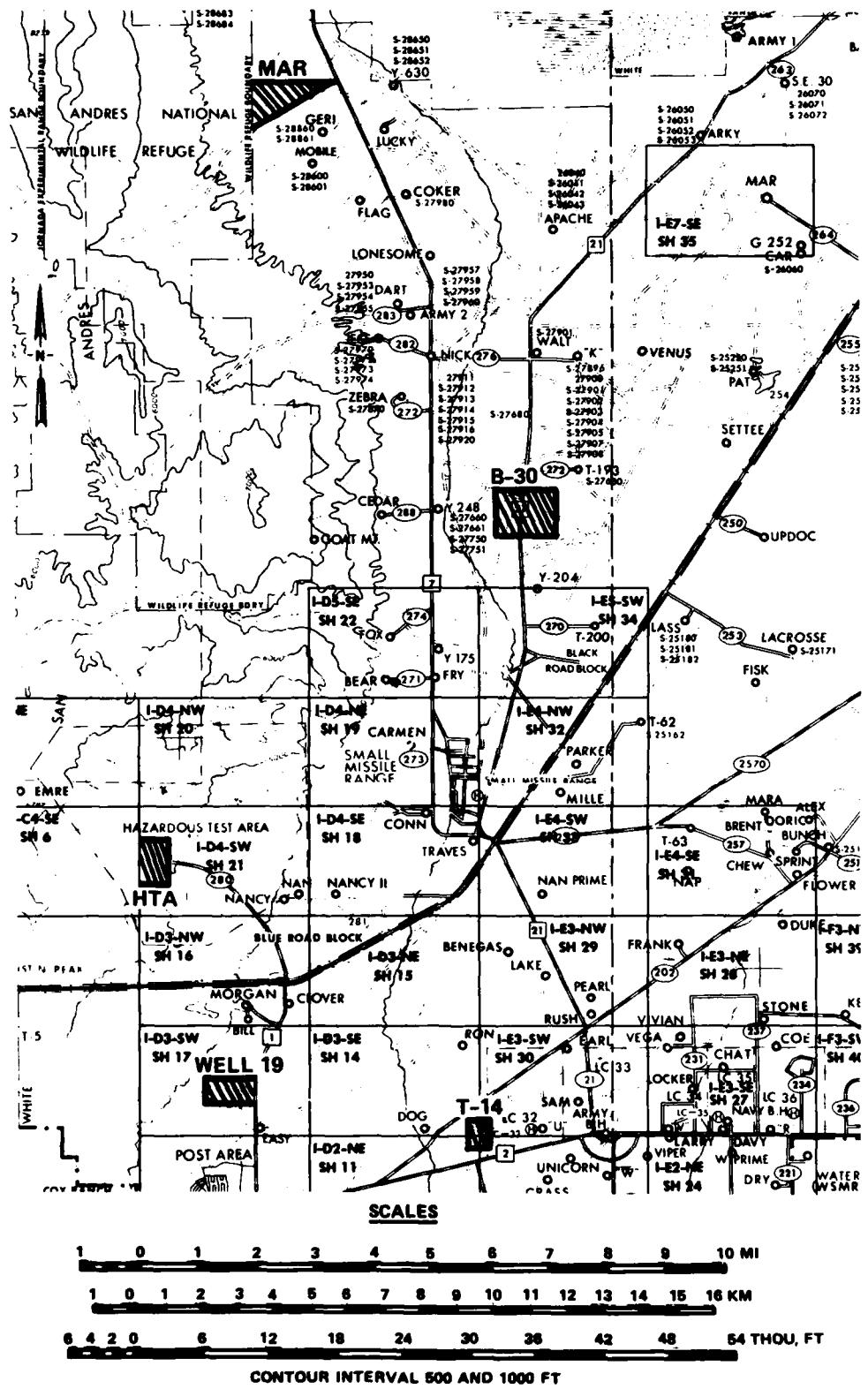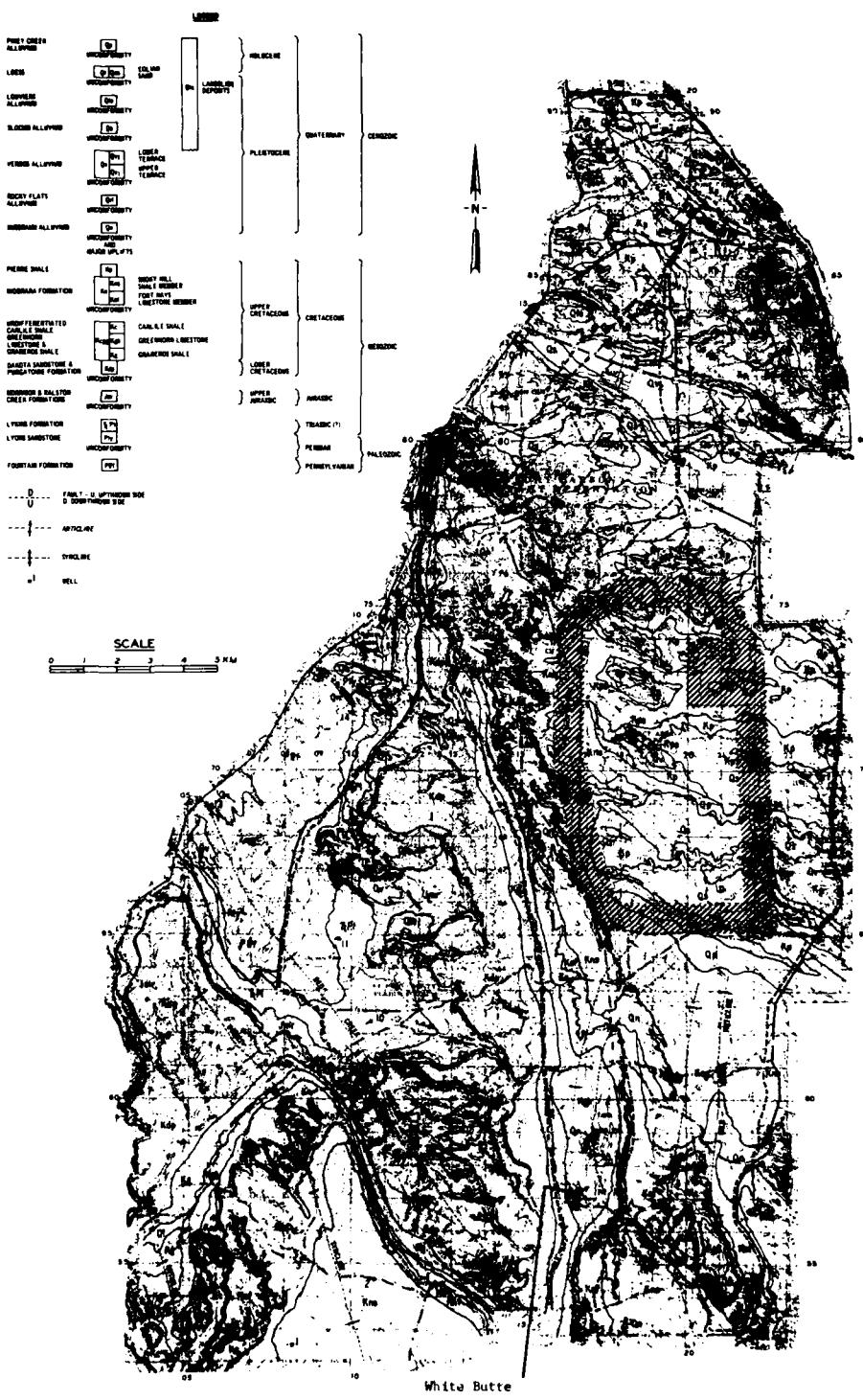
PLATE 2

APPENDIX A: LETTER REPORT, SCHLUMBERGER SOUNDINGS,

by R. J. BISDORF, USGS

Introduction

1. In an effort to evaluate different resistivity interpretation
techniques and computer programs, selected data from the White Sands,
New Mexico, and Fort Carson, Colorado, sites were sent to Mr. Robert
Bisdorf and Dr. Adel Zohdy of the U. S. Geological Survey for assessment
and comment. The cooperation and assistance provided by Mr. Bisdorf and
Dr. Zohdy prior to and during the course of this investigation are
greatly appreciated.

2. Information provided in this appendix includes output from
the automatic inversion program and documentation for soundings conducted
at locations HTA-1, B-30, SW-19, and T-14 at the White Sands, New Mexico,
site.

3. The data indicated that soundings S-2 and S-3 at the Fort
Carson, Colorado, site are approaching a resistivity layer from one side
(Figure A1). The cusps appear to be due to more than just faulting,
although the capability to model these interesting two-dimensional prob-
lems is not yet available. The rest of the soundings do not appear to
be affected by lateral effects; however, since they are probably oriented
parallel to strike, the effects would be subtle.
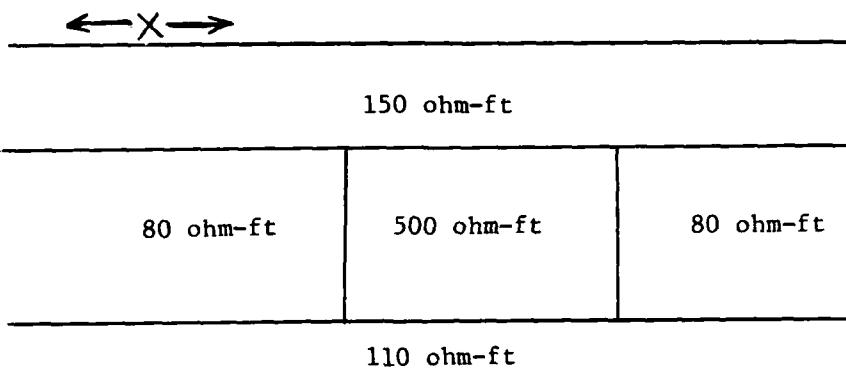
Figure A1.   Possible explanation for fat cusps,
Fort Carson data

A1

Inversion of Schlumberger Sounding Data

4. The sounding curves and their automatic inversions are given
in Figures A2-A17. All the sounding data were automatically processed
and interpreted (Zohdy 1973, 1975) as shown in the graphs. The curves
were interpreted on a Hewlett-Packard (HP) 9845B desktop computer using
a program based on the program of Zohdy (1973). The HP program was
modified to use O'Neill coefficients (O'Neill 1975) in place of Ghosh
coefficients (Ghosh 1971).

5. For each sounding, the data include:

    <u>a</u>. A log-log plot of the field data points, in which the "0"'s
represent the individual data points. The AB/2 electrode
spacings have been converted to metres. Each set of data
points that was made with the same potential electrode
spacing (MN) is connected with a solid line. Measurements
were made at the fixed MN/2 spacings of 2, 6, 20, 60, 200,
and 600 ft.

    <u>b</u>. A tabulation of the AB/2 electrode spacings in metres and
the corresponding apparent resistivities in ohm-m.

    <u>c</u>. A log-log plot of the output of the automatic inversion
program in which:

        (1) The continuous curve represents the shifted-digitized
field curve (Bisdorf and Zohdy 1979).

        (2) The step-function curve represents the distribution
of interpreted-true resistivity with depth.

        (3) The "S"'s represent points on the theoretical
sounding curve for the given distribution of
resistivity with depth. These points are given to
show how well the interpreted model fits the shifted-
digitized curve.

    <u>d</u>. A tabulation of the interpreted depths in metres and the
interpreted resistivities in ohm-m.

6. For some soundings the original inversion did not fit the
digitized data very well. These soundings were smoothed in a fashion
that would help automatic inversion to fit parts of the data better.
These soundings have "-S" appended to their names (Figures A6-A9 and
A14-A17).

A2

SCHLUMBERGER ELECTRODE SPACING (AB/2), IN FEET
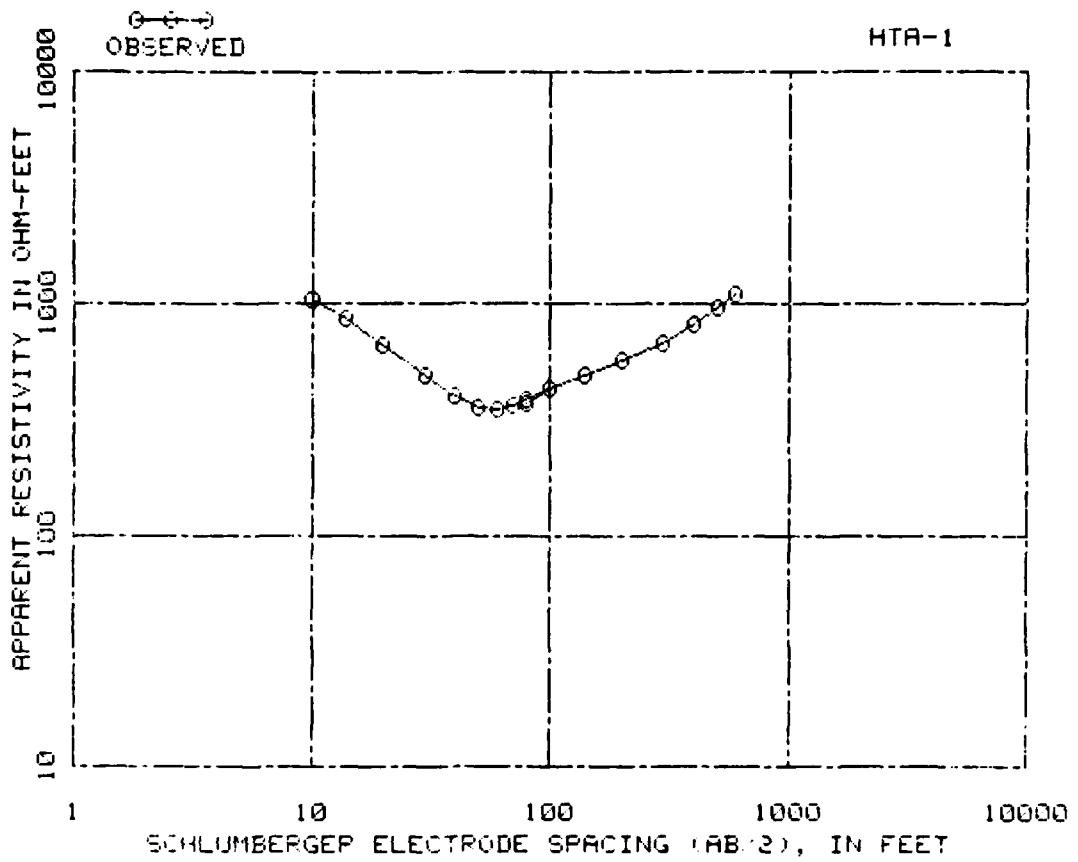
AB/2 IN FEET	OBSERVED RESISTIVITY IN OHM-FEET
10.00	1037.00
14.00	857.00
20.00	662.00
30.00	491.00
40.00	397.00
50.00	358.00
60.00	348.00
70.00	361.00
80.00	382.00
100.00	429.00
80.00	373.00
100.00	435.00
140.00	491.00
200.00	569.00
300.00	682.00
400.00	824.00
500.00	966.00
600.00	1106.00

Figure A2. Data for sounding HTA-1

Figure A3. Data inversion for HTA-1
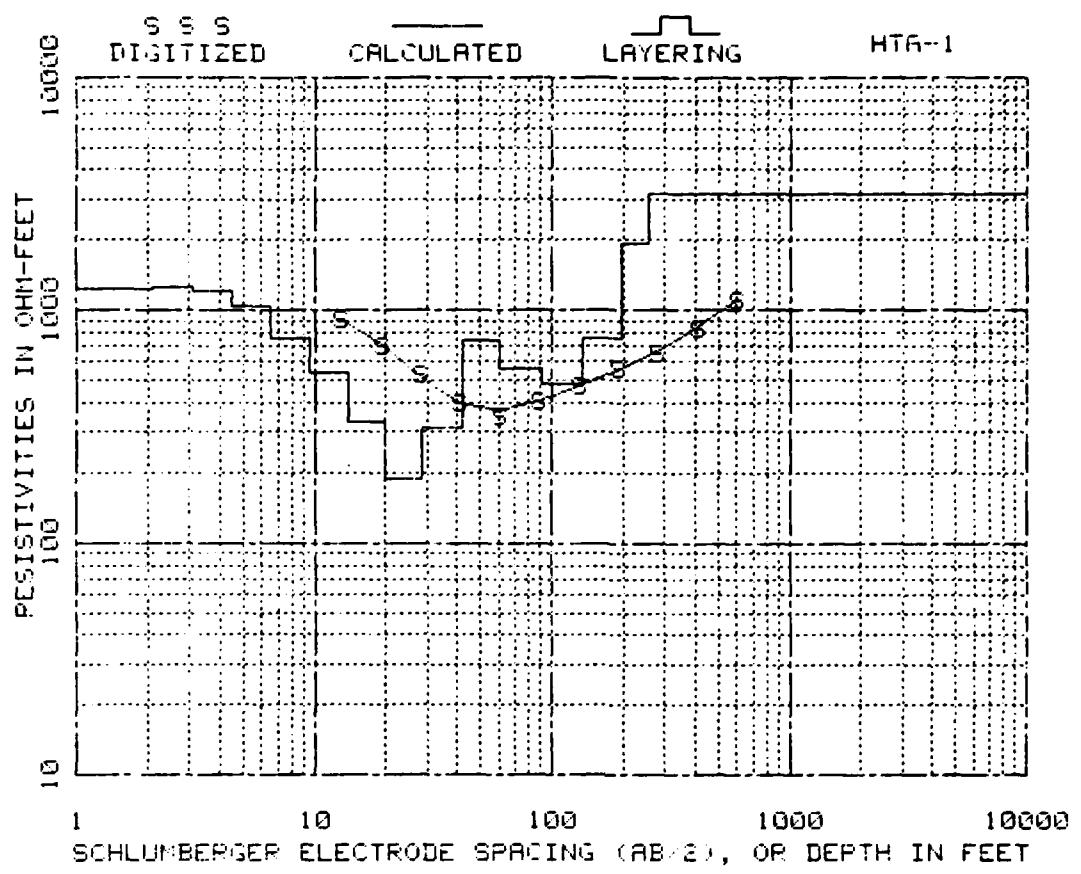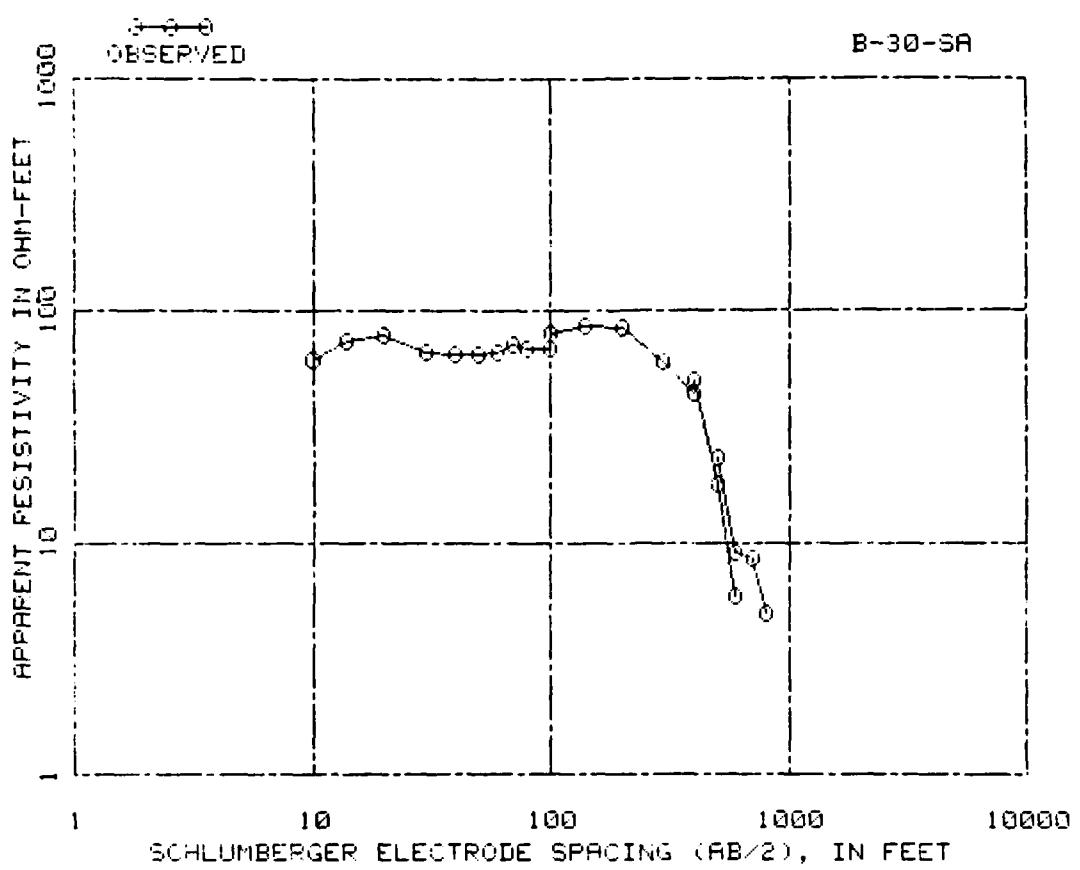
DEPTH IN FEET	RESISTIVITY IN OHM-FEET	DEPTH IN FEET	RESISTIVITY IN OHM-FEET
.97	1231.66	19.89	331.92
1.42	1229.65	28.13	188.09
2.09	1238.22	42.39	314.52
3.07	1252.60	60.01	748.01
4.50	1219.85	90.35	561.33
6.59	1035.17	135.70	479.68
9.60	756.63	197.71	757.64
13.90	539.87	257.15	1921.70
		3281093.77	3181.60

A4

OBSERVED

APPARENT RESISTIVITY IN OHM-FEET

SCHLUMBERGER ELECTRODE SPACING (AB/2), IN FEET

AB/2 IN FEET	OBSERVED RESISTIVITY IN OHM-FEET	AB/2 IN FEET	OBSERVED RESISTIVITY IN OHM-FEET
10.00	61.30	140.00	86.10
14.00	75.00	200.00	84.90
20.00	78.00	300.00	61.00
30.00	65.90	400.00	44.30
40.00	65.80	400.00	50.20
50.00	65.70	500.00	17.90
60.00	66.70	600.00	5.87
70.00	71.60	500.00	23.30
80.00	69.60	600.00	8.99
100.00	69.60	700.00	8.58
100.00	79.60	800.00	5.01

Figure A4. Data for sounding B-30

A5
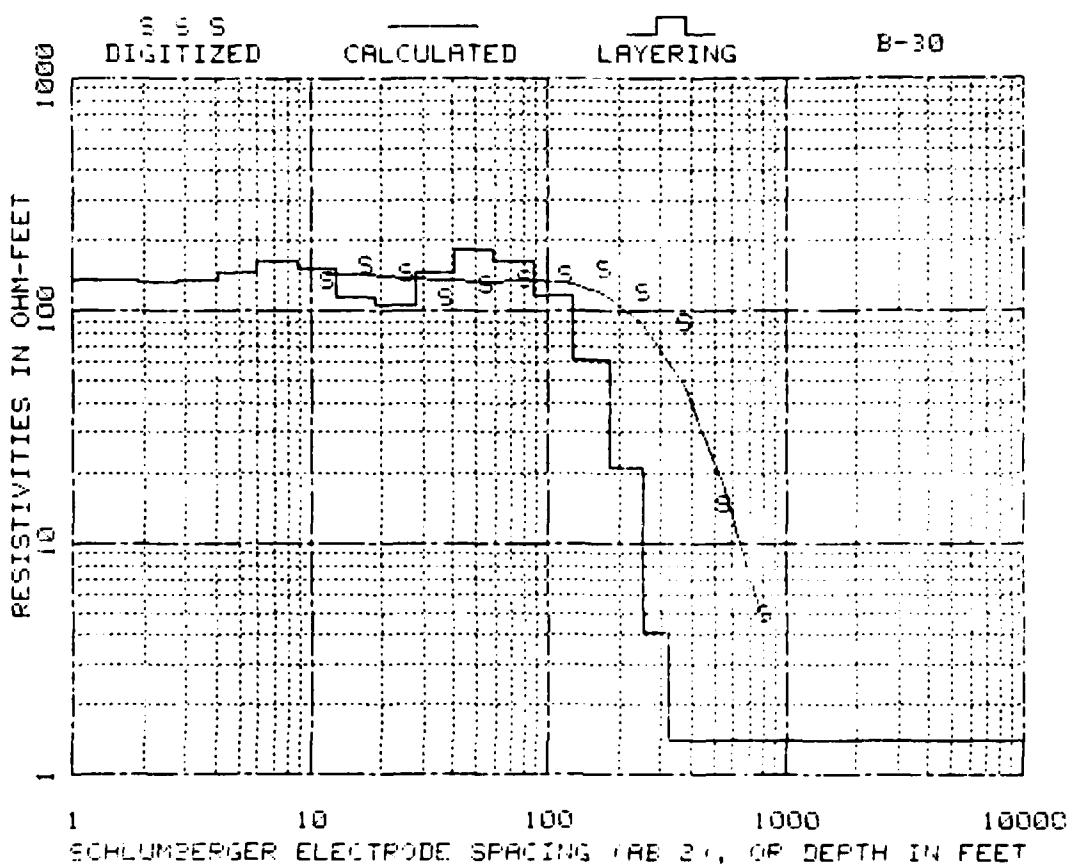
DEPTH IN FEET	RESISTIVITY IN OHM-FEET	DEPTH IN FEET	RESISTIVITY IN OHM-FEET
.88	135.17	27.71	107.14
1.29	135.19	40.63	147.64
1.90	134.56	59.08	183.04
2.78	133.88	87.03	162.94
4.09	135.72	127.91	116.50
5.99	146.85	184.13	61.87
8.77	164.18	251.90	21.14
12.89	152.79	317.75	4.08
18.89	115.27	3281154.36	1.41

Figure A5. Data inversion for B-30
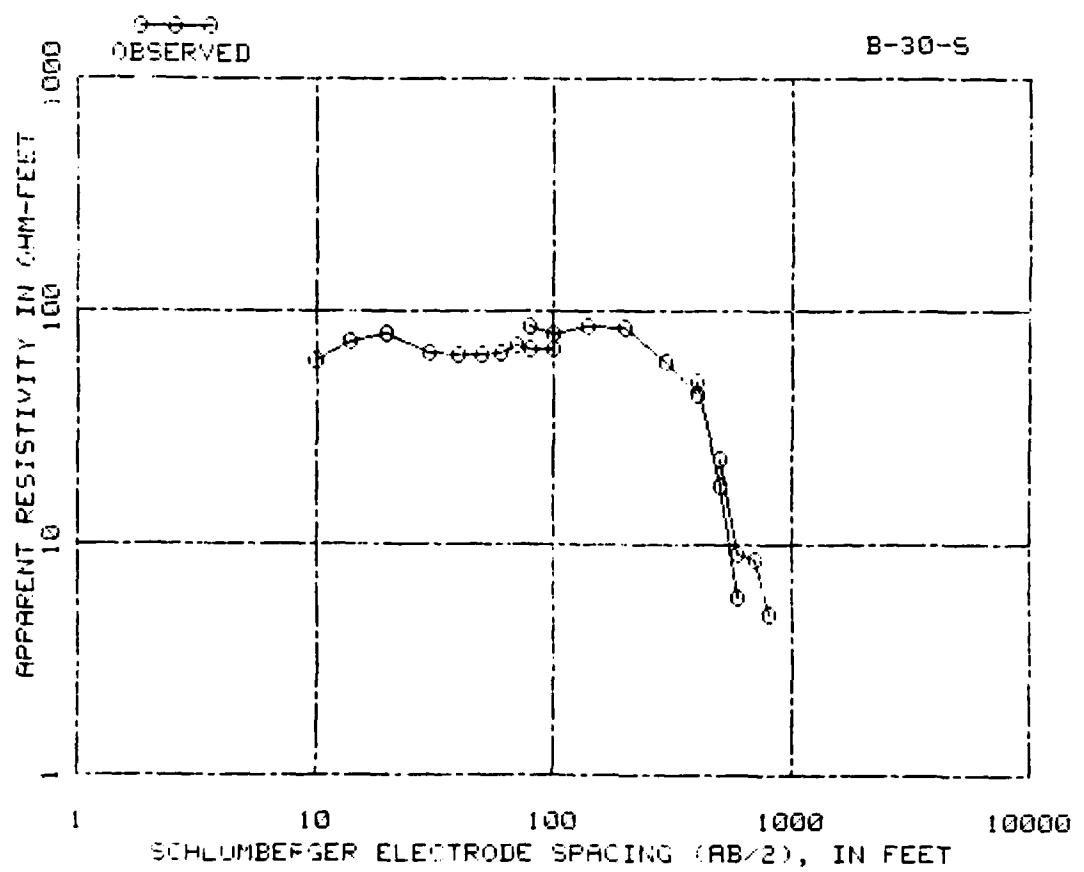
A6

OBSERVED   B-30-S

APPARENT RESISTIVITY IN OHM-FEET

SCHLUMBERGER ELECTRODE SPACING (AB/2), IN FEET

AB/2 IN FEET	OBSERVED RESISTIVITY IN OHM-FEET	AB/2 IN FEET	OBSERVED RESISTIVITY IN OHM-FEET
10.00	61.30	100.00	79.60
14.00	75.00	140.00	86.10
20.00	80.20	200.00	84.90
30.00	65.90	300.00	61.00
40.00	65.80	400.00	44.30
50.00	65.70	400.00	50.20
60.00	66.70	500.00	17.90
70.00	71.60	600.00	5.87
80.00	69.60	500.00	23.30
100.00	69.60	600.00	8.99
90.00	87.10	700.00	8.58
		800.00	5.01

Figure A6. Smoothed data (1) for sounding B-30
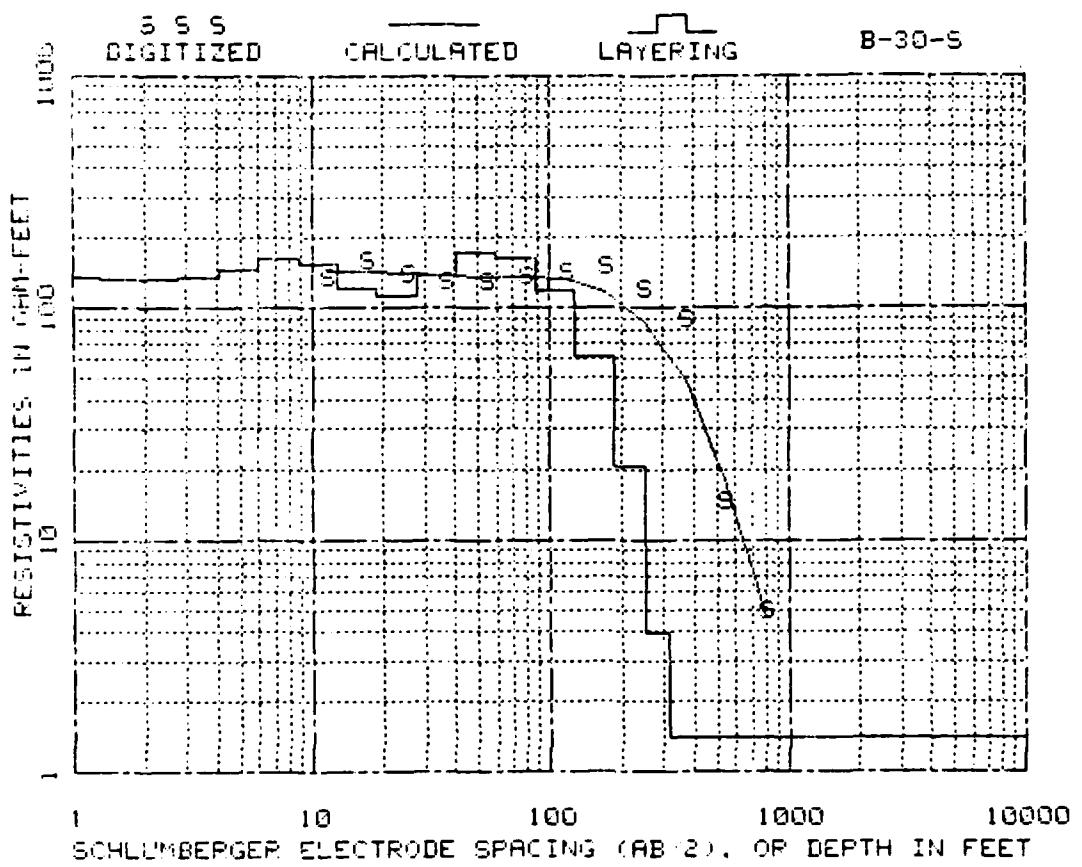
A7

Figure A7. Data inversion for smoothed B-30 data in Figure A6
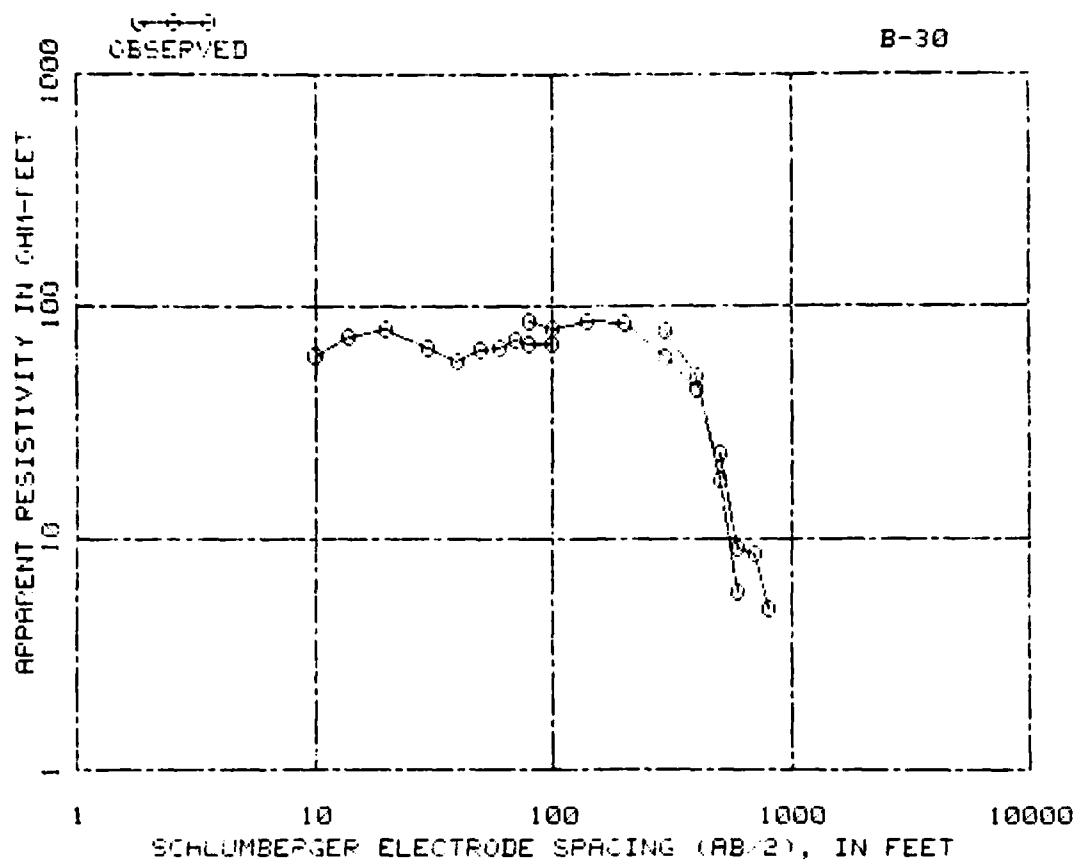
DEPTH IN FEET	RESISTIVITY IN OHM-FEET	DEPTH IN FEET	RESISTIVITY IN OHM-FEET
.88	134.90	27.72	111.80
1.29	134.93	40.73	138.55
1.90	134.31	59.42	171.37
2.78	133.66	87.31	164.75
4.09	135.38	128.24	118.41
5.99	146.48	184.41	61.57
8.77	164.34	251.77	20.71
12.89	156.07	316.99	3.96
18.90	122.14	3281153.60	1.41

A8

OBSERVED

APPARENT RESISTIVITY IN OHM-FEET

SCHLUMBERGER ELECTRODE SPACING (AB/2), IN FEET

AB/2 IN FEET	OBSERVED RESISTIVITY IN OHM-FEET	AB/2 IN FEET	OBSERVED RESISTIVITY IN OHM-FEET
10.00	61.30	140.00	86.10
14.00	75.00	200.00	84.90
20.00	80.20	300.00	61.00
30.00	65.90	400.00	44.30
40.00	58.00	300.00	78.80
50.00	65.70	400.00	50.20
60.00	66.70	500.00	17.90
70.00	71.60	600.00	5.87
80.00	69.60	500.00	23.30
100.00	69.60	600.00	8.99
90.00	87.10	700.00	8.59
100.00	79.60	800.00	5.01

Figure A8. Smoothed data (2) for sounding B-30

A9
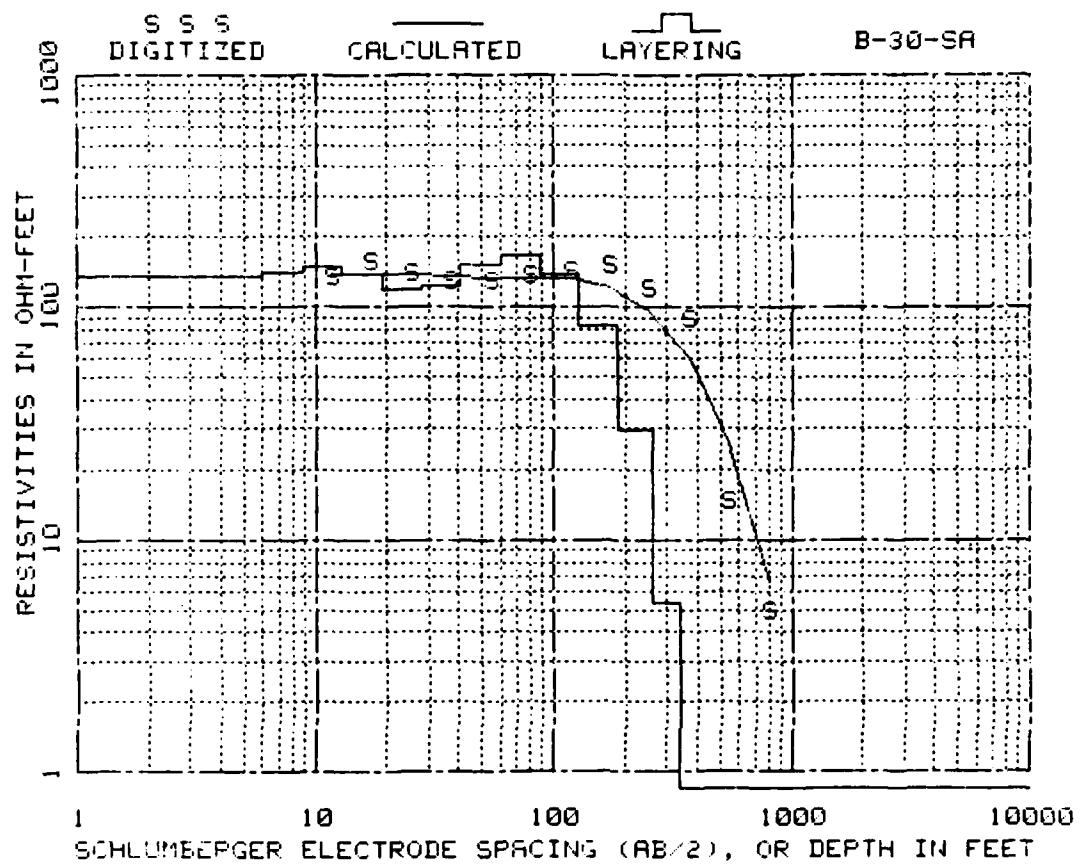
DEPTH IN FEET	RESISTIVITY IN OHM-FEET	DEPTH IN FEET	RESISTIVITY IN OHM-FEET
.88	135.37	27.81	119.35
1.29	135.44	40.83	122.91
1.90	135.46	59.78	152.30
2.78	135.22	87.45	167.26
4.09	134.61	128.63	138.77
6.00	135.61	187.36	82.51
8.80	141.35	262.21	29.87
12.92	147.79	338.07	5.38
18.96	137.59	3281174.63	.85

Figure A9. Data inversion for smoothed B-30 data in Figure A8
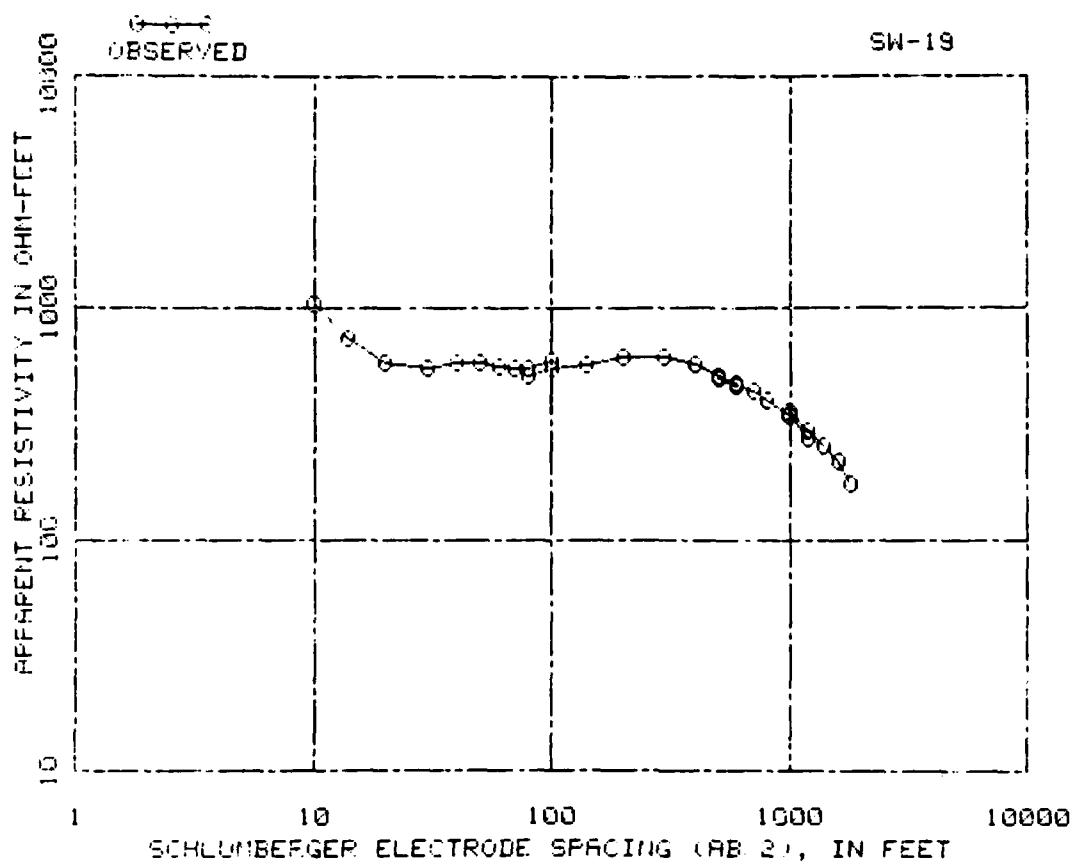
A10

OBSERVED SW-19

APPARENT RESISTIVITY IN OHM-FEET

SCHLUMBERGER ELECTRODE SPACING (AB 2), IN FEET

AB/2 IN FEET	OBSERVED RESISTIVITY IN OHM-FEET	AB/2 IN FEET	OBSERVED RESISTIVITY IN OHM-FEET
10.00	1045.00	300.00	611.00
14.00	749.00	400.00	568.00
20.00	581.00	500.00	514.00
30.00	551.00	600.00	478.00
40.00	582.00	500.00	505.00
50.00	586.00	600.00	468.00
60.00	563.00	700.00	442.00
70.00	548.00	800.00	402.00
80.00	548.00	1000.00	346.00
100.00	591.00	1200.00	274.00
50.00	508.00	1000.00	355.00
100.00	549.00	1200.00	297.00
140.00	571.00	1400.00	254.00
200.00	622.00	1600.00	219.00
		1800.00	175.00

Figure A10. Data for sounding SW-19

A11

S S S
DIGITIZED   CALCULATED   LAYERING   SW-19

RESISTIVITIES IN OHM-FEET

10000
1000
100
10

1   10   100   1000   10000
SCHLUMBERGER ELECTRODE SPACING (AB/2), OR DEPTH IN FEET
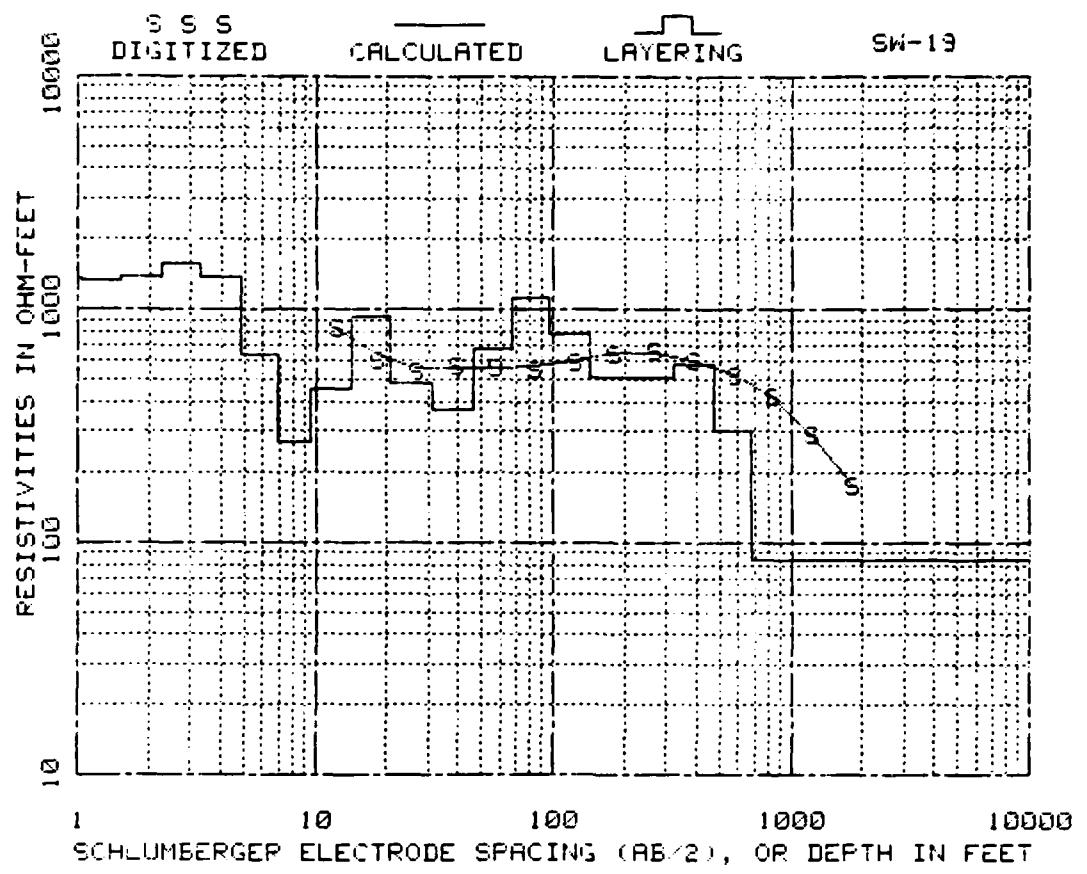
DEPTH IN FEET	RESISTIVITY IN OHM-FEET	DEPTH IN FEET	RESISTIVITY IN OHM-FEET
.71	1388.38	31.14	486.29
1.04	1366.53	46.02	368.94
1.52	1329.53	67.90	679.37
2.24	1381.84	95.97	1117.55
3.28	1566.32	144.16	791.76
4.81	1391.71	214.41	513.43
6.88	634.58	318.32	508.02
9.46	267.24	471.93	580.71
14.24	452.49	682.88	301.05
20.30	931.48	3281520.50	84.51

Figure A11.   Data inversion for SW-19
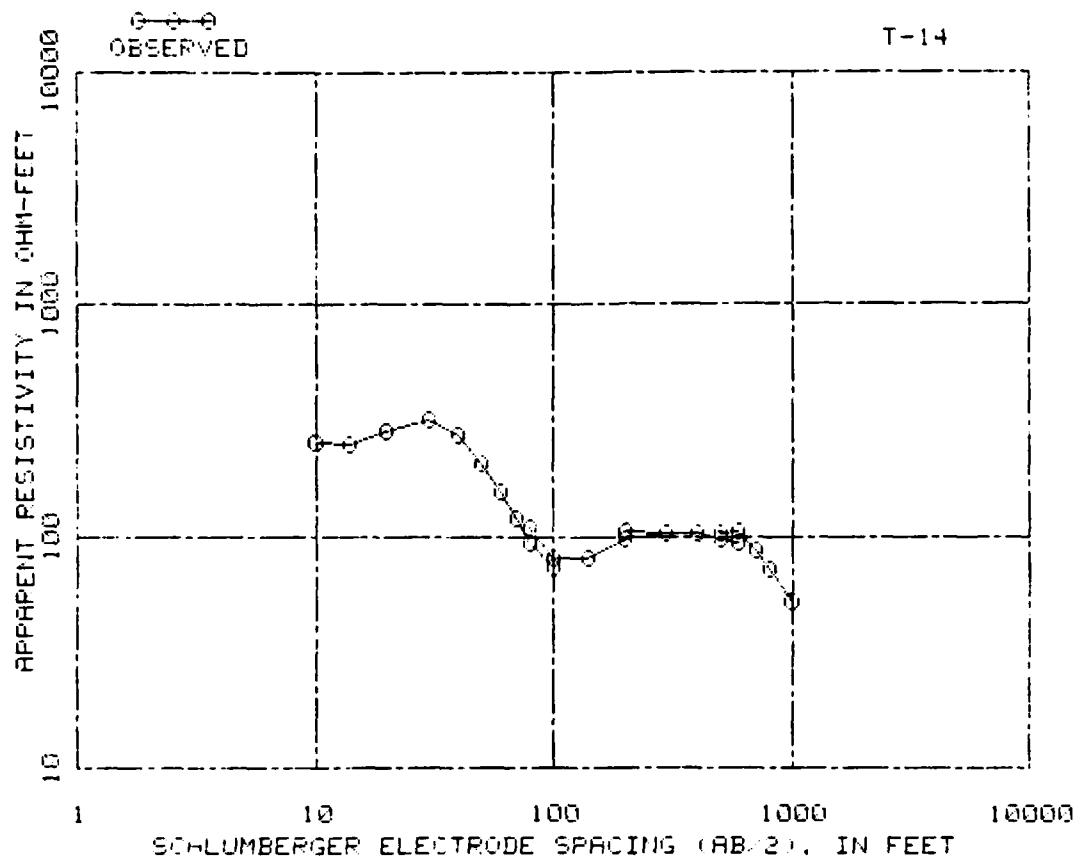
A12

OBSERVED

APPARENT RESISTIVITY IN OHM-FEET

SCHLUMBERGER ELECTRODE SPACING (AB/2), IN FEET

AB/2 IN FEET	OBSERVED RESISTIVITY IN OHM-FEET	AB/2 IN FEET	OBSERVED RESISTIVITY IN OHM-FEET
10.00	256.00	140.00	80.70
14.00	249.00	200.00	98.10
20.00	286.00	300.00	104.00
30.00	319.00	200.00	105.00
40.00	276.00	300.00	104.00
50.00	208.00	400.00	104.00
60.00	157.00	500.00	98.40
70.00	120.00	600.00	93.20
80.00	93.90	500.00	103.00
100.00	73.00	600.00	106.00
80.00	109.00	700.00	87.70
100.00	80.20	800.00	71.90
		1000.00	52.20

Figure A12. Data for sounding T-14

A13
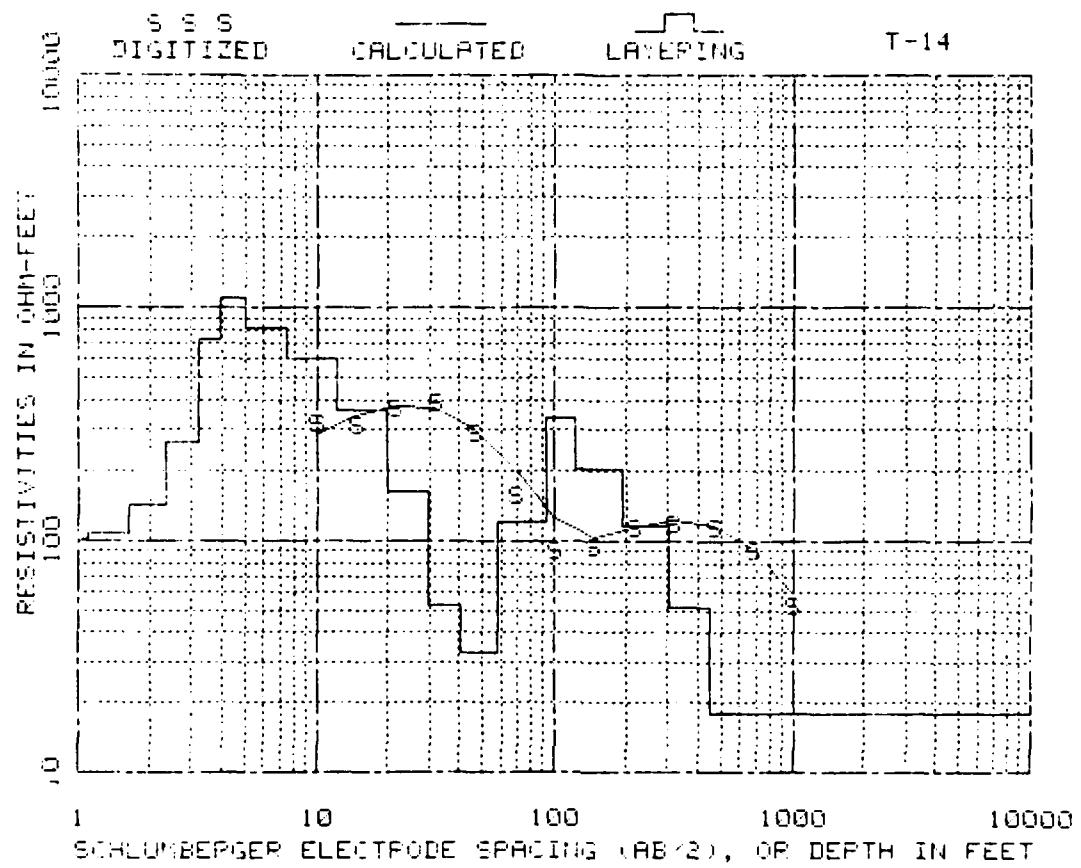
DEPTH IN FEET	RESISTIVITY IN OHM-FEET	DEPTH IN FEET	RESISTIVITY IN OHM-FEET
.75	105.41	19.79	365.78
1.10	102.13	29.64	160.91
1.62	107.93	40.79	52.41
2.35	141.26	58.35	32.85
3.23	264.85	92.17	120.33
3.97	735.54	123.09	340.49
5.00	1096.30	193.85	203.09
7.49	812.88	303.84	116.41
12.28	604.14	447.05	51.52
		3281283.66	18.08

Figure A13.   Data inversion for T-14
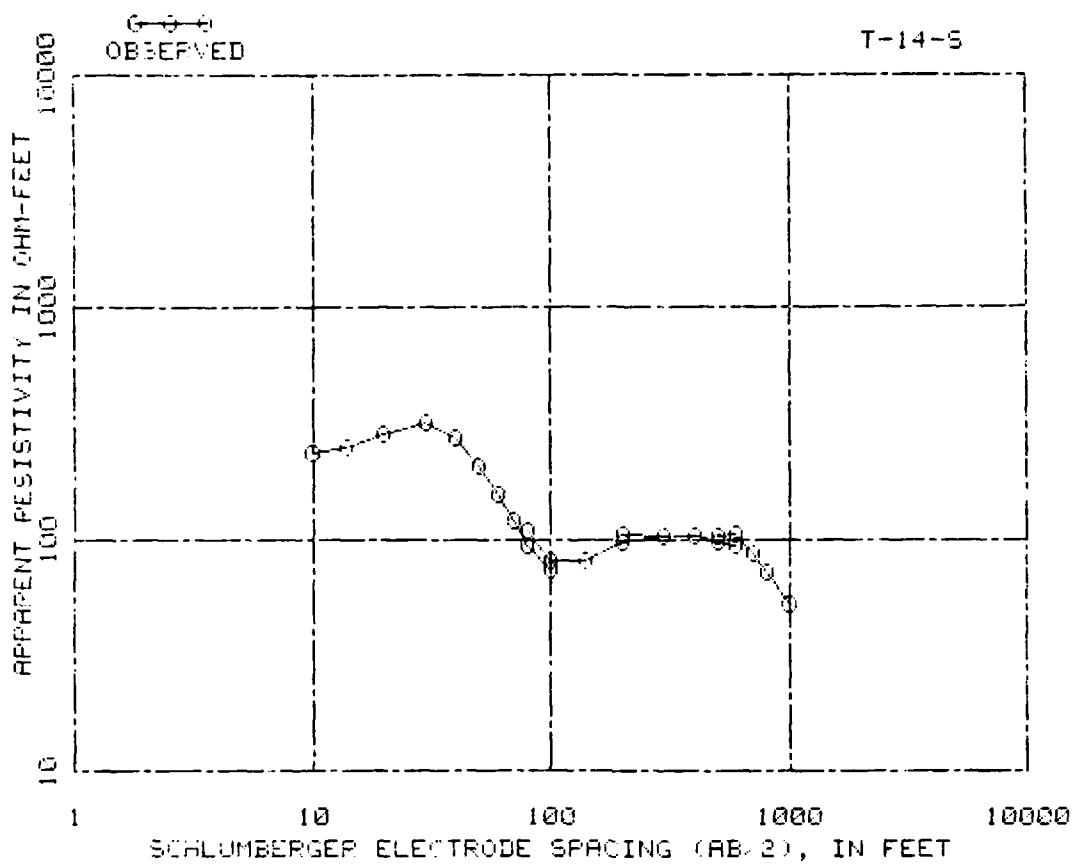
A14

OBSERVED

APPARENT RESISTIVITY IN OHM-FEET

10000
1000
100
10

1   10   100   1000   10000

SCHLUMBERGER ELECTRODE SPACING (AB/2), IN FEET

AB/2 IN FEET	OBSERVED RESISTIVITY IN OHM-FEET	AB/2 IN FEET	OBSERVED RESISTIVITY IN OHM-FEET
10.00	235.00	140.00	80.70
14.00	249.00	200.00	98.10
20.00	286.00	300.00	104.00
30.00	319.00	200.00	105.00
40.00	276.00	300.00	104.00
50.00	208.00	400.00	104.00
60.00	157.00	500.00	98.40
70.00	120.00	600.00	93.20
80.00	93.90	500.00	103.00
100.00	73.00	600.00	106.00
80.00	109.00	700.00	87.70
100.00	80.20	800.00	71.90
		1000.00	52.20

Figure A14. Smoothed data (1) for sounding T-14

A15
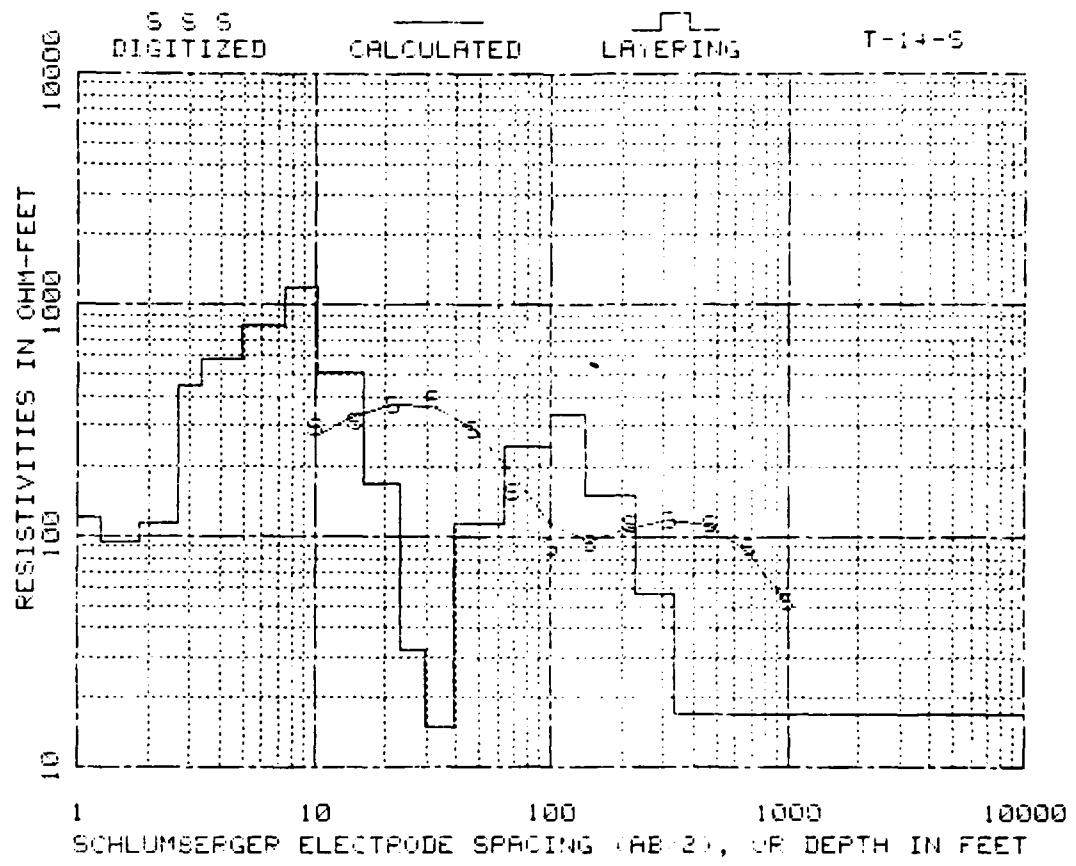
DEPTH IN FEET	RESISTIVITY IN OHM-FEET	DEPTH IN FEET	RESISTIVITY IN OHM-FEET
.58	119.34	16.14	512.83
.85	132.92	23.27	169.13
1.24	119.01	29.51	32.36
1.82	93.68	34.17	14.78
2.67	112.62	43.17	112.95
3.36	445.72	99.78	243.50
4.94	578.13	141.47	335.98
7.51	812.91	226.76	150.69
10.32	1182.99	335.64	56.30
		3281172.26	16.89

Figure A15. Data inversion for smoothed T-14 data in Figure A14
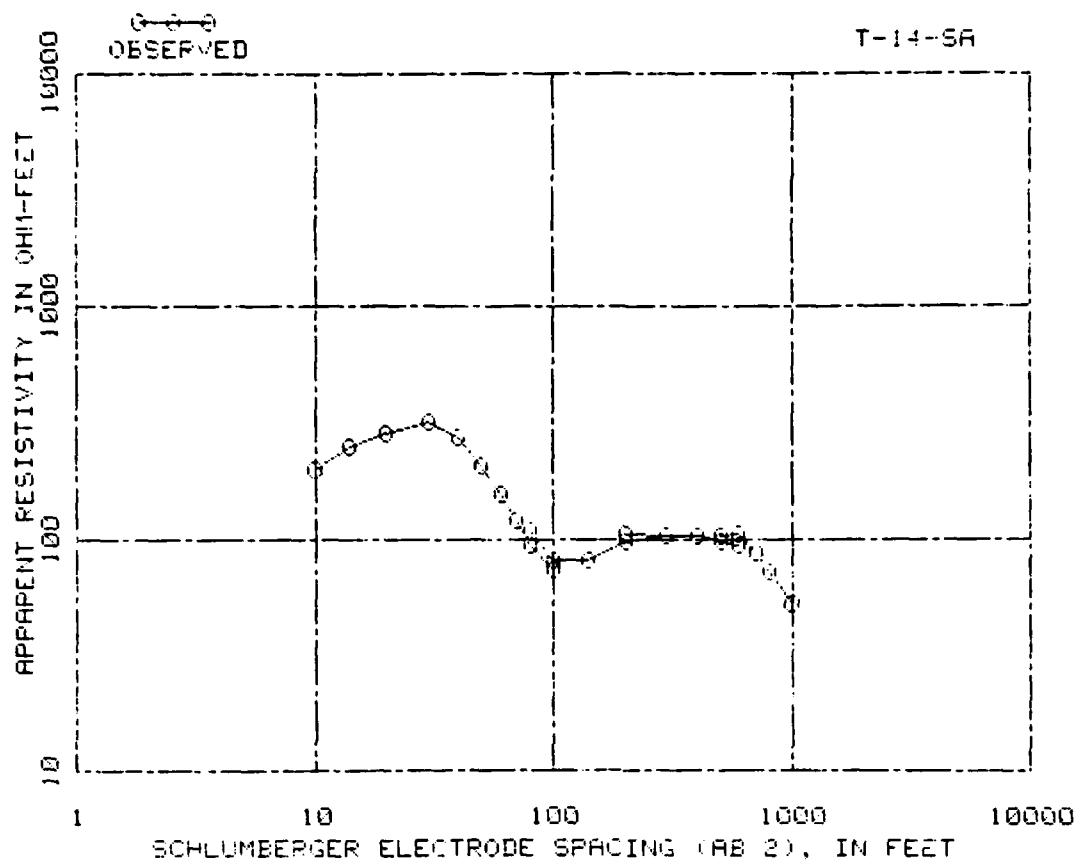
A16

Figure A16. Smoothed data (2) for sounding T-14

AB/2 IN FEET	OBSERVED RESISTIVITY IN OHM-FEET	AB/2 IN FEET	OBSERVED RESISTIVITY IN OHM-FEET
10.00	200.00	140.00	80.70
14.00	249.00	200.00	98.10
20.00	286.00	300.00	104.00
30.00	319.00	200.00	105.00
40.00	276.00	300.00	104.00
50.00	208.00	400.00	104.00
60.00	157.00	500.00	98.40
70.00	120.00	600.00	93.20
80.00	93.90	500.00	103.00
100.00	73.00	600.00	106.00
80.00	109.00	700.00	87.70
100.00	80.20	800.00	71.90
		1000.00	52.20

A17

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  S S S              ─────              ┌─┐
  DIGITIZED          CALCULATED          LAYERING          T-14-SA
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RESISTIVITIES IN OHM-FEET

SCHLUMBERGER ELECTRODE SPACING (AB/2), OR DEPTH IN FEET

DEPTH IN FEET	RESISTIVITY IN OHM-FEET	DEPTH IN FEET	RESISTIVITY IN OHM-FEET
.44	148.61	12.18	991.02
.65	114.87	18.61	381.85
.95	180.12	24.92	79.42
1.38	199.73	30.24	13.96
2.02	107.82	49.15	38.36
2.97	104.48	62.43	344.87
3.88	413.82	107.39	234.88
5.73	599.86	157.95	336.41
8.54	867.24	252.92	127.84
		3281089.53	22.15

Figure A17.   Data inversion for smoothed T-14 data in Figure A16

A18

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O'Neill, D. J. 1975. "Improved Linear Filter Coefficients for Application in Apparent Resistivity Computations," Bulletin, Australian Society Exploration Geophysics, Vol 6, No. 4, pp 104-109.

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